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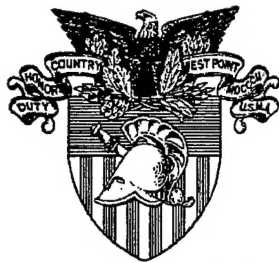
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14. ABSTRACT

As the Army transforms itself into the 21st century, a number of new requirements arise in response to the need for a lighter force that is more rapidly deployed. The concept of trading heavy forces for information requires a substantial increase in the need for situational awareness and use of sensor technologies for remote reconnaissance collection on the battlefield. High quality situation awareness can be achieved using various types of networked sensors to flow information to a common operating picture console at the battlefield commander's disposal. Networked unattended ground microsensors (UGS) represent an integral part of the US Army's capabilities for covering Beyond Line of Sight (BLOS) and Non-line of Sight (NLOS) areas.

This report presents a methodology for understanding the relationships that exist between critical performance measures associated with UGS sensor clusters and the levels of sensor density in such a cluster. Using the concept of diminishing marginal output productivity in the face of constrained operating environment, this methodology can help Objective Force designers make informed decisions concerning the UGS base unit TOE package.

Following a detailed discussion of related work and technical information pertinent to this study, we present an in-depth systems engineering functional decomposition and functional flow analysis that illuminates many of the functional interdependencies affecting cluster design. Based on this analysis, we next introduce both the new methodology along with estimated functional tradeoff relationships and marginal output functions for various cluster performance measures. Finally, we introduce a process for validating the proposed tradeoff relationships in concert with several key information requirements for a human-in-the-loop simulation designed for such a purpose.

The new methodology presented in this study enables FCS Objective Force researchers to gain a new perspective on the interdependencies and interconnectedness of the UGS systems and demonstrates an effective means of identifying the appropriate UGS TOE levels for this force.

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ABSTRACT

As the Army transforms itself into the 21st century, a number of new requirements arise in response to the need for a lighter force that is more rapidly deployed. The requirement for medium sized armament vehicles that fit onto C-130 airplanes, and smaller deployed forces that are capable of covering a greater area within a complex environment, increasing the need for command, control, surveillance and reconnaissance capabilities in order to ensure the success of any mission. The concept of trading heavy forces for information requires a substantial increase in the need for situational awareness and use of sensor technologies for remote reconnaissance collection on the battlefield. High quality situation awareness can be achieved using various types of networked sensors to flow information to a common operating picture console at the battlefield commander's disposal. Networked unattended ground microsensors (UGS) represent an integral part of the US Army's capabilities for covering Beyond Line of Sight (BLOS) and Non-line of Sight (NLOS) areas.

This report presents a methodology for understanding the relationships that exist between critical performance measures associated with UGS sensor clusters and the levels of sensor density in such a cluster. Using the concept of diminishing marginal output productivity in the face of constrained operating environment, this methodology can help Objective Force designers make informed decisions concerning the UGS base unit TOE package.

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The new methodology presented in this study enables FCS Objective Force researchers to gain a new perspective on the interdependencies and interconnectedness of the UGS systems and demonstrates an effective means of identifying the appropriate UGS TOE levels for this force.

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> Lamm, Gregory A. *Assessing and Managing Risks to Information Assurance: A Methodological Approach.* Systems Engineering Department, University of Virginia, Charlottesville, VA, DTIC number: ADA391850, May 2001.
>
> Haimes, Yacov Y., Thomas A. Longstaff, and Gregory A. Lamm. *Balancing Promise and Risk to Information Assurance in Joint Vision 2020.* Military Operations Research Society (MORS). MS. NO. 01-08.

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> P.J. Driscoll and H.D. Sherali. 2001. "On tightening the relaxations of Miller-Tucker-Zemlin formulations for asymmetric traveling salesman problems." To appear in *Operations Research.*
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Acknowledgements

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Section 1.   Introduction

1.1.   Overview

The U.S. Army Chief of Staff has committed the forces to perhaps the most significant restructuring in the history of the Army. This Objective Force structuring is being driven by the need for a lighter ground force, measured both in raw numbers of components and amount of required logistic support, that is capable of rapidly responding to a wide spectrum of threats to U.S. interests anywhere in the world.

Inherent in the design requirements for such an Objective Force is the need to identify and exploit system equivalences for critical force functions and components that directly contribute to mission success. It is well understood that such equivalences provide the basis for establishing design guidelines when trading heavy armor for lighter vehicles, a major design requirement of the Objective Force. However, they are equally as vital to identify when the design goal is to replace unit personnel with systems capable of performing the same battlefield tasks. These equivalent systems are intended to create information dominance over adversaries by adding levels of responsiveness, precision, and battlespace awareness that vastly exceeds those available through other means.

One manner of achieving such a dominant battlespace awareness for ground force commanders is through the complete integration of sensor networks throughout the entire range of Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) functions envisioned for the Objective Force and capable of delivering mission critical information in both Beyond Line of Sight (BLOS) and Non-line of Sight (NLOS) areas of the battlefield. Unattended ground micro-sensors (UGS) represent one suite of assets available to the Objective Force commanders for achieving and exploiting this high level of battlespace awareness.

UGS come in various sizes and forms. Each individual sensor may contain one or more types of sensing capability (seismic, acoustic, magnetic, image, and Forward Looking Infrared (FLIR)). UGS are small, relatively low cost to manufacture, operationally robust, and capable of performing information gathering missions on the battlefield for extended, although limited, periods of time. This operational time is driven both by the life of the on-device battery and the

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power requirements for various operations the sensor is asked to perform. Battery life is a factor constraining sensor communications as well.

Sensor *clusters*, comprised of three to five individual sensors (nodes) linked through efficient, low-range communications, are capable of being deployed by several means (e.g., air, artillery, and hand). Sensor *fields* are then constructed by positioning several clusters within geographic proximity to each other and then linking the communications pathways of these clusters together into a sensor *network*. Networked sensors are capable of performing a host of missions (e.g., general surveillance, early warning, target acquisition, target tracking, battle damage assessment) against a wide range of targets.

The ultimate purpose of constructing sensor networks is to facilitate rapid remote target detection, location, tracking, engagement and battle damage assessment in regions of the battlespace well beyond those that have been directly exploitable by ground force commanders. An ability to identify and engage enemy forces and their resources well before they can do the same to friendly forces gives unit commanders more complete battlespace knowledge, thereby directly enhancing both their *decision cycle*, by shortening it beyond the enemy's ability to insert disruptive measures into it, and the *decision quality* by reducing elements of uncertainty associated with accurately assessing an evolving enemy situation.

UGS operate in all-weather conditions around the clock. However, terrain, weather, background noise, and time of day all affect their precision. The level of precision ultimately has an impact on the resulting accuracy of the *information* produced by an UGS sensor cluster. The performance of an UGS sensor cluster is affected by environmental factors such as these, as well as device factors such as number, type, orientation, and reliability, among others.

UGS have the potential to not simply augment current operational capabilities, but to actually replace elements in the Objective Force whose battlespace functions can be more effectively performed by UGS. In this manner, sensor technologies can change the way the Army does business, potentially change its operational art, and certainly change the way that Army forces are configured for battle. For example, some scout functions in support of target acquisition by the Reconnaissance, Surveillance, Targeting and Acquisition (RSTA) squadron might be performed at higher precision, lower risk, and longer duration by UGS.

Deciding whether of not it makes sense to substitute UGS for human force elements requires an understanding of the *functional tradeoff relationships* that exist between these

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elements, the levels at which equivalence is achieved, and the human response in the context of battlespace operations to having made such a replacement. Providing a quantitative response to these requirements is the focus of this study. Our goal is to exploit the resulting information in order to provide design guidance concerning both the effective deployment levels of UGS on the battlefield and practical levels of TOE assignment for these devices.

The objectives of this study are six-fold:

1. Develop a methodology for determining key tradeoff relationships, determining their points of diminishing returns, and how to make networked UGS decisions with the information;
2. Introduce key functional tradeoffs that exist between the number of sensors and performance metrics in BLOS and NLOS deployment for clusters of homogeneous UGS types;
3. Propose a validation plan for converting theoretical tradeoff relationships to their actual tradeoff values through simulation results and identifying points of diminishing returns for each sensor performance measure the can subsequently support an optimization of these measures using multi-objective tradeoff analysis;
4. Identify equivalence points between personnel and sensor clusters within the context of the typical mission set (intelligence) for the RSTA squadron;
5. Prescribe ideal deployment levels and TOE assignment levels for general force configuration guidelines;
6. Provide a foundation for continued research examining the information flow on an UGS-supported sensor-to-shooter (STS) network as it relates to sensor mix and decision quality issues.

This report is organized as follows. Section (1.2) presents a survey of related research associated with UGS deployment and tradeoff studies. Section (1.3) introduces the general framework used to develop functional tradeoff relationships in this study. Section 2 then applies a Systems Engineering and Management Process (SEMP) to the major UGS types in order to illuminate key operational dimensions and performance metrics that need to be imbedded in tradeoff representations. Using the results of the previous sections, Section 3 proposes specific functional tradeoff curves and equivalence points against performance metrics. Section 4 presents a validation process for refining these functional tradeoff curves. Finally, in Section 5 we present our conclusions, recommendations, and comments on extensions and further research ideas.

1.2. Related Research

The literature is extensive regarding technical aspects of sensor design and technologies (see [1], [31], [43], [4], [29], [24], and [6]). However, there appears to be only a limited number of tradeoff studies focusing on the operational impact that UGS will have on the future battlefield.

In one such effort, Tietenberg [44] discusses the relevant concept of diminishing marginal productivity, concluding that in the presence of a fixed factor (terrain), successively larger additions of a variable factor (individual UGS in this case) will eventually lead to a decline in the marginal productivity of the variable factor. Haimes [18] presents a comprehensive discussion of multi-objective tradeoff analysis in modeling and decision making, stressing the importance of incorporating risk into this analysis. Myers and Montgomery [36] demonstrate the usefulness of incorporating the desirability function developed by Derringer and Suich [1980] when multiple performance measures must be optimized. This desirability function facilitates setting priorities and desires on the performance measures within the optimization process. We use this desirability function framework in our research to perform multiobjective tradeoffs and optimization analysis because it is able to capture and represent many of the design elements needed for any optimization routine.

The Army Research Lab (ARL) - Sensor and Electron Devices Directorate (SEDD) is doing a great deal of work with sensors. Hopkins et al.[19] describe the ongoing Warrior Extended Battlespace Sensors (WEBS) program consisting of applied research into small, low cost, networked unattended battlefield sensor systems that can passively detect, locate, track, and identify personnel, ground vehicles, aircraft, cruise missiles, artillery, mortar fire, and other battlefield targets. In a related study following his earlier effort, Hopkins [21] further presents concepts, issues and initiatives concerning networked sensors for the battlefield. Gerber [15] increased general understanding of UGS by providing a comprehensive treatment of sensor characteristics and their associated maximum range and classification capabilities. In an independent effort, Wilson [50] and [51] greatly enhanced the toolset used to assess the performance of acoustic sensors in a variety of environmental settings by introducing a MATLAB-based prototype decision aid called the Acoustic Battlefield Aid (ABFA). This development provided researchers with an easy to use, graphical interface software tool for rapid assessment of performance configurations.

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As is evident in the sequel, we propose to validate the proposed tradeoff functions introduced in this study using a sensor simulation called Comprehensive Mine and Sensor Server (CMS^2) within a main simulation program called Fort Knox SAF. The core UGS sensor models used in the simulation were developed by Wilson [50] and Moran et al. [35] in conjunction with Army Research Lab (ARL) and NVESD. Although the CMS^2 links with either Fort Knox SAF or OTB SAF and supports deployment of sensors and smart anti-personnel and anti-tank mines, for the purposes of validation we concern ourselves exclusively with the sensors portion of CMS^2.

CMS^2 represents UGS as a baseline cluster consisting of four sensor nodes, an imager, short range communication capabilities and one gateway node with long range communications capability. The data resulting from the CMS^2 integration in the Fort Knox SAF is appropriate for use in validating our proposed tradeoff functions for two reasons. Fort Knox SAF is the main simulation program used by the U.S. Army for man-in-the-loop decision-making combat simulation exercises. Secondly, because Fort Knox SAF portrays a notional future force structure set in the 2015 to 2020 timeframe using a main entity size element called a Unit of Action (UofA), it meshes well with most force configurations currently being considered for the Objective Force. The UofA concept was first introduced by Paul [38] in the context of a study on the Future Combat Command and Control Networked Sensors for the Objective Force Simulation Study. Relevant to our efforts, Paul's study illuminated several key objectives, how the simulation accomplished them, and presented issues of concern as to the performance of the scout elements using the sensor tools.

In a particularly interesting survey study at the Operations Research Center (ORCEN) at the U.S. Military Academy, Willis and Davis [49] highlight the historic uses of sensors, desired sensor functions and capabilities, and the developing sensor technologies that will enable commanders to effectively employ several future force configurations in decisive engagements with less risk to military personnel. McCassey [33] extended this work by addressing a variety of deployment options and introducing a framework for an optimization approach capable of resolving a host of issues surrounding the deployment of UGS.

At the time of this report, there are several ongoing complementary studies that either directly support or extend the objectives of this research effort. McGinnis et al. [12] and [34] are working an extensive redesign initiative focusing on effectively restructuring headquarters

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elements for the Objective Force to facilitate their compatibility with compressed decision cycles and rapid exploitation of technology-delivered information. In order to resolve the issue of effective mix of UGS types in battlefield deployment, Driscoll and Pohl [11] are developing a stochastic-based methodology of assessing the decision quality of information produced by and within UGS-supported sensor-to-shooter (STS) networks. This study is particularly relevant because the results provide both design guidance as to the proper mix of UGS for TOE purposes and insights as to where and when actions must be taken to maintain a high level of decision quality in a STS network. Such a methodology is naturally scalable to address both non-UGS STS networks and joint interoperable STS networks as well. West [48] is proposing a novel time-sensitive risk analysis associated with several decision processes affecting battlefield operations for the Objective Force. Finally, Kwinn et al. [27], [28] both directly and indirectly consider the use of UGS as defined in this study's objectives to facilitate an Objective Force conceptual design that will avoid imbedding tacit vulnerabilities into the force structure.

1.3. Functional Tradeoff Relationships

Recall that the principal problem we address in this study focuses on identifying the ideal number of sensors to deploy in a cluster intended to cover a one kilometer square area of the battlefield in either NLOS or BLOS areas of interest (AOI). This one kilometer square area therefore represents the minimum AOI for an UGS cluster deployment. Larger AOI can simply be expressed as scalar multiples of this base unit. The base unit cluster is also an appropriate Table of Equipment (TOE) sensor package concept to use here.

In light of this fixed base unit, we note that determining the number of sensors to deploy as a cluster unit appeals to the law of diminishing marginal productivity [32]. This law states that in the presence of a fixed factor, successively larger additions of a variable factor will eventually lead to a decline in the marginal productivity of the variable factor. This phenomenon is most commonly encountered in production and manufacturing, an environment in which labor units play the part of the variable factor and the output is product-based. As the amount of labor units dedicated to a product increases, the product output increases but at a decreasing rate.

A similar phenomenon should underlie sensor performance because of the direct analogy between structural components of both systems, especially when a sensor cluster is viewed as an information manufacturing system. We therefore hypothesize that by representing the various

dimensions of output performance as functions of a single variable factor, in this case sensor density, we can use these points of diminishing marginal returns to determine an efficient allocation of sensors to a cluster.

We generalize the concept of diminishing marginal productivity to the UGS cluster issue as follows: in the presence of a fixed one-kilometer deployment area, successively larger additions of individual sensors will eventually lead to a decline in the marginal productivity as measured by the applicable dimensions of performance for the sensor cluster. An individual sensor is analogous to a unit of labor in the sense that it does the 'work' associated with the valued output product of a sensor cluster: information.[1]

As an increase in sensor density (sensors per one kilometer square area, or equivalently sensors per cluster) drives the marginal productivity of the sensor cluster down to a point where it falls below the total average productivity, per capita sensor value will decline with further increases in sensor density, just as it does for the case of labor. This means that, in terms of the information coming out of a sensor cluster (detection, classification, identification, and possibly tracking), it is possible to over-design against performance measures, thereby squandering valuable resources and adding risk to the force.

Two characteristics of UGS clusters support the application of this generalized law in the UGS context. First, the physical geometry defining the operational environment of a sensor cluster dictates that only a finite number of targets can be in detectable proximity to individual sensors. Increasing the number of sensors assigned to a cluster eventually results in redundant detection, classification and/or identification information being generated into the information network. To the point of Lines of Bearing (LOB) intersection (2-sensor LOB) or triangulation (3-sensor LOB), depending upon whether movement tracking or targeting is of interest

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[1] As an important aside, it is this information manufacturing conceptual framework that naturally links the two issues of determining an ideal number of sensors and an ideal mix of sensors for a TOE cluster. By viewing the information generated by an UGS cluster as an information product, we demonstrate in a separate study that the ideal mix of sensors (once the ideal number of sensors has been determined) can be determined by invoking the Equimarginal Principle. Applied to the UGS mix environment, this principle states that when the same information product (e.g. cluster identification report) is being generated or manufactured by two or more sensor element types (e.g. seismic, acoustic production units), in order to get the maximum total output for the cluster, the level of individual UGS sensor types composing the TOE mix should be allocated in such a way that the marginal productivity of each sensor is the same in each unit of production (sensor element type).

respectively, a certain amount of redundancy is called for. Past this point, however, redundant information flow exacerbates information overload on the network, whose resolution requires sophisticated filtering to extract vital situational awareness components. In this sense, there naturally exists a point where further confirmatory evidence concerning a potential target is simply not required.

Secondly, aggregation processes that filter and combine low-level detection data nullify the effects of confirmatory evidence beyond a preset threshold level needed to process a target. For an UGS sensor cluster, such an aggregation process first takes place at individual sensor nodes where low-level classification of a detected object occurs, and then again at master nodes which decide on the identity of a potential target by clustering individual node classification data and forwarding a single cluster report as to the target's identity into the communications network.

Intrinsic in our analysis is an assumption that an increase in per capita sensor cluster information products will, at some point, be restrained by sensor density increases. This directly implies that economies of scale are not available in the setting of sensor cluster design as described herein. Simply put into the vernacular, "more is not always better" and there will come a point where "too many cooks spoil the soup." Economies of scale would occur if increases in sensor density lead directly to a more-than-proportionate increase in sensor cluster output as indicated by performance measures. Allowing for dynamic expansion in the size of the base unit AOI for UGS deployment would facilitate economies of scale here, but the very nature of doing so would run contrary to the intent of this study. That is, if there is no fixed base deployment AOI unit for UGS and a Unit-of-Action is given the latitude to create ad hoc clusters of any size as needed, then the problem of how many UGS should comprise a TOE cluster loses relevancy. Moreover, such a situation would unnecessarily complicate communication pathways and efficient routing schemes.

Technological progress provides one means of escaping the law of diminishing marginal productivity. If the state of technical knowledge on how to most effectively compose and employ sensor clusters uniquely advances over time, then one or more of the output productivity functions associated with a sensor cluster could shift so that the marginal productivity of a sensor cluster would continue to increase as the sensor density increased, even though the base unit AOI is unchanged from the one kilometer square AOI considered in this study. Such a situation is

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likely to be encountered in a mature system rather than early in the design process, as is the case with UGS within FCS.

Once individual points of diminishing marginal productivity are identified for each performance measure, there are two ways we can determine an efficient sensor density to allocate to a base unit cluster. If the number of performance output measures as a function of sensor density is small, and the marginal productivity decreases from the start in a monotonic fashion, we can determine an efficient allocation by plotting all the marginal productivity functions associated with the performance output measures on the same graph. The point nearest to a point of common intersection identifies an efficient allocation level. If the number of performance output measures were large, and/or the marginal productivity increases during an initial interval and then reaches a point whereby it begins to decrease, an efficient allocation can be determined by optimizing the sensor cluster and field performance at each UGS structural level using multi-objective tradeoff methods to determine an ideal balance across all tradeoff categories. It is this latter approach we explore in this study, reserving the analysis of composite marginal productivity functions for a follow-on study.
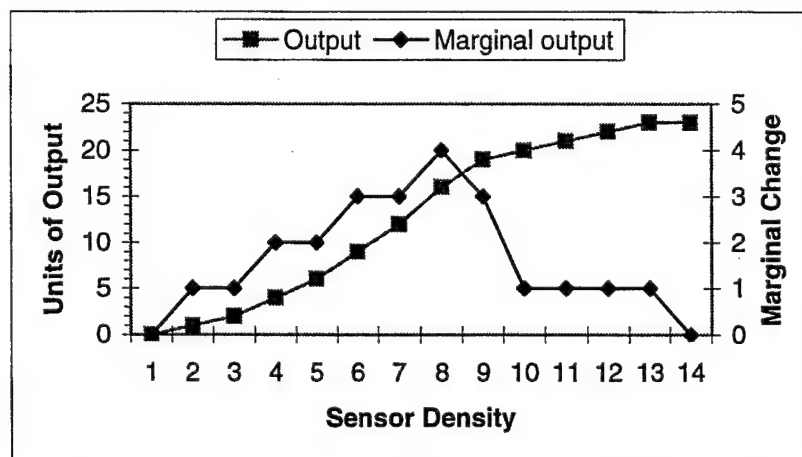
Figure 1: Marginal productivity and output levels as sensor density varies

As an example of how a point of diminishing marginal productivity can be identified in the context of sensor performance, consider the hypothetical tradeoff function for one performance measure as depicted in the S-curve shown in Figure 1. A point of diminishing marginal productivity can be seen to occur where this output function changes its orientation from convex to concave at the 8-sensor density level. As can be seen by the graph of the

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marginal output, this location corresponds to the point where the marginal rate of output reaches a maximum and begins to decrease. Beyond this level, the cluster's total productivity continues to increase but at a decreasing rate. That is, the rate of productivity begins to decline in the face of increases in the number of UGS allocated to the cluster. Consequently, in the context of this hypothetical performance output measure, any allocation of sensors beyond the level of 8 would represent an over-investment in design. Taken alone, this would seem to indicate that we should assign 8 sensors to a base unit cluster. However, we note two additional points of consideration that affect a recommended allocation level: 1) Most obvious is that all performance measures must be taken into account when designing the level of sensors to allocate to a base unit cluster and 2) A more subtle consideration is that the existence of any non-zero probability of sensor failure during deployment would necessarily increase the recommended level so as to build in a small amount of redundancy into the design. It is, after all, the ideal operational design levels we are interested in and not simply the pre-deployment levels. Anticipating approximately a 10% deployment failure rate, the recommended base unit allocation for this hypothetical case would be 9 sensors.

The multiple objective tradeoff optimization technique is used in this study to aggregate the affects of all performance tradeoff functions is based on a method introduced by Derringer and Suich [1980]. We likewise make use of a *desirability function* that enables us to impose various priorities and preferences on the system performance measures, which are thereafter directly exploited by an optimization procedure.

The desirability function takes into account all n performance measures and chooses the conditions x on the design variables that maximize an objective function given by:

$$D = (d_1 \times d_2 \times .. \times d_n)^{\frac{1}{n}},$$

where n is the number of performance measures and d_i reflects the desirable ranges for each performance measure i, $i = 1, 2, ...n$. This technique requires that each performance measure be assigned an upper and lower bound as well as an objective that defines the desired direction of optimization (*i.e.*, minimize or maximize). The resulting objective function $D(d_1, d_2, ..., d_n)$ is then optimized over a common objective by changing the sign of the associated d_j as necessary (minimize d_j = maximize $- d_j$).

In general, this particular formulation is computationally challenging to solve since the objective function's mathematical structure defines a nonlinear, non-convex integer programming problem. Although a handful of effective solution techniques exist for solving this type of problem [26], we adopt a rather simple heuristic approach for the case of analyzing UGS clusters in this study because of the low-dimensionality of the problem. For larger problem instances such as the extension of this work to address multi-layered, multi-service STS networks, more sophisticated approaches will be required.

The heuristic approach we use relies on simple enumeration within a spreadsheet model. By enumerating and evaluating all possible discrete values of d_j within D, it is a straightforward process to identify those that simultaneously maximize the desirability function.

The particular shape adopted for each initial performance tradeoff curve was based on estimation from the literature, much in the same way that prior probability distributions for Bayesian networks are estimated as a starting point for experimentation that will further refine the shape parameters of these distributions. We likewise propose a follow-on validation study for this same purpose, as described in Section 5 of this report. Consequently, the estimated functional tradeoff curves do well to illustrate the methodology we present but are naturally lacking in sufficient specificity to make conclusive sensor design level recommendations without further validation.

We highlight two sensor performance output measures for this study because of their obvious importance to the FCS design: Sensor Cluster Performance and Sensor Field Performance. Section 2 presents an overview of key technical aspects of UGS that provide a basis for all of the functional tradeoff relationships presented in Section 3.

Section 2.   The UGS System
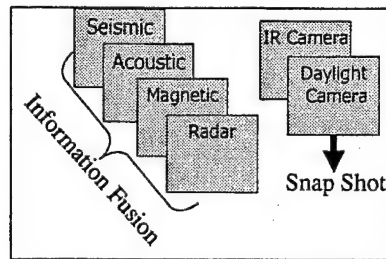
Figure 2: UGS Sensor Types

2.1.   Suite of Unattended Ground Sensors

The current suite of unattended ground sensors (UGS) for the U.S. Army is comprised of acoustic, seismic, magnet, and radar sensing devices along with a limited number of infrared and daylight still-image cameras. These devices are deployed on the battlefield in clusters that are interconnected by low and high range communications networks. For FCS and Objective Force purposes, they are used for obtaining non-line of sight (NLOS) and beyond line of sight (BLOS) situational awareness. The UGS that we focus on in this study are ones envisioned to be under the functional control of the battalion level battlefield commander. The deployment region for these sensors is approximately 2 – 20 kilometers outside of the unit location of such a battalion [3].

For a RSTA squadron, UGS act as an intelligence multiplier by extending the eyes and ears of human scouts beyond their physical limits. Their innate ability to collect and transmit data and information rapidly provides near real time threat detection and targeting. UGS are useful for preventing unintended close combat, increasing SA for threat susceptible areas such as flanks, high speed avenues of approach, low probability avenues of approach and the battalion's rear area. Early warning sensor missions require sensor clusters to be placed along enemy avenues of approach as far forward as possible in order to exploit the ability of UGS fields to provide maximum reaction time to evolving battlefield dynamics.

In addition to intelligence gathering, UGS are also intended for use in sensor-to-shooter (STS) networks. However, their inability to completely distinguish between hostile, friendly and noncombatant activity remains a major limitation of the unattended sensors yet to be overcome. Due to this current deficiency, other surveillance assets (e.g.,

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Predator image) are typically relied upon to confirm target information prior to engagement by network-linked weapon platforms. This strategy reduces the potential information leverage gain that UGS can provide. Despite this shortcoming, UGS offer a unique ability for rapidly cueing other target acquisition sources without requiring human intervention to manage the process. It is this ability to rapidly iterate through detection, classification, identification, confirmation, tracking, engagement, and damage assessment that promises a very high level of responsiveness sufficient enough to desire their integration into Objective Force and FCS design.

Like all technology devices deployed on the battlefield, the performance of UGS may be hampered by environmental factors apart from enemy intervention. Table 1 summarizes the possible effects that different terrain features and environmental aspects may play on UGS, thus degrading their accuracy and effectiveness.

Table 1: Environmental Effects on Sensors [47]

Feature	Effects
Soil	Detection radius (especially seismic)
Ambient Interference (i.e., noise due to earth tremors, surf action, power lines)	Degrades quality & detection capabilities (especially seismic & magnetic)
Vegetation	May interfere with radio LOS communications May hinder antenna placement
Elevated Areas	May degrade detection radius
Weather	May degrade sensor detection radius
Atmospheric Effects	May degrade detection radius May degrade LOS communications
Day/Night	Effects Seismic sensor detection radius (night allows sound to travel further)
Wind	May hinder both seismic and acoustic detection

2.1.1. Acoustic Sensors

The current suite of acoustic sensors provides passive, non-line of sight detection and low-level classification capabilities for a number of enemy battlefield targets. The approximate maximum effective range of an acoustic sensor depends upon which of the three general target groups it is addressing: 50 meters for personnel talking or making audible noises, 250 meters for wheeled vehicles and 700 meters for tracked vehicles. Acoustic sensors are omni-directional with a detection radius of 360 degrees. The probability of detection for all three types of targets is approximately 95 percent while the

probability of classification for all three types of targets is approximately 80 percent [15]. The combination of multiple sensors provides classification of unique objects.

Acoustic sensors operate by collecting sound waves in the air generated by potential targets. Sound waves (acoustic energy waves) occur when matter vibrates at a particular frequency. Frequencies between 20 Hz and 20 kHz are detectable by the human ear but acoustic sensors focus on detecting targets below the 150Hz range (20-150Hz) [19]. The frequency of a sound is directly related to its wavelength. Low-frequency acoustic waves have a long wavelength (e.g., fog horn, tank engine) and can travel further compared to high-frequency acoustic waves (e.g., high-note on piano, conversations).

Terrain features (e.g., trees, hills, power lines) and environmental factors (e.g., weather, wind, humidity, running water, time of day) may either assist or hinder the collection capabilities of acoustic sensors. Terrain and environmental factors have a pronounced effect on the detection distances for acoustic sensor clusters because they can deflect, confound or destroy acoustic signals, thereby degrading the accuracy of the target information.

After acoustic sensors sense the sound waves that are emitted by potential targets, the sensors form a digital signature of the potential target by collecting analog waves and compare that result to other preset digital sound signatures. Additionally, each sensor may pass the signature to other sensors (i.e., cluster or node sensor manager) for more complete analysis. The resulting classification information is then transmitted as a single cluster report by the sensor communications network gateway to a centralized processing point. There this information is combined with other acoustic sensor information enabling analysts to estimate the target's position by measuring the time of arrival of sound waves at several known sensor locations [1].

Acoustic sensors can also perform target identification based on the characteristics of the detected sound waves by comparing their wave signatures against known profiles [19].

2.1.2. Seismic Sensors

The current suites of seismic sensors are passive, non-line of sight sensors that provide unique detection and low-level classification capabilities for equipment over a user-adjustable detection range based on the type of target. Seismic sensors are used as trip or cue sensors in a sensor cluster because they are generally low cost and have a long battery life. Seismic sensors cue other sensors based on preset detection and classification thresholds, and conduct cueing procedures based on sensor algorithm protocols. Seismic sensors are best used to fill the detection void created by adverse acoustic propagation conditions.

The approximate maximum effective range of seismic sensors on the three target groups noted earlier are: 30 meters for personnel (if they are talking or making audible noises), 250 meters for wheeled vehicles and 500 meters for tracked vehicles. The range of detection is 360 degrees and the probability of detection for all three types of targets is approximately 95 percent while the probability of classification for all three types of targets is approximately 95 percent [15].

Seismic sensors operate by collecting multiple wave type vibrations with varied arrival structures from the ground such as the disturbances generated by moving vehicles and personnel. The sensors generally detect ground vibrations from targets operating below the 20 Hz range [42]. Ground waves (seismic energy waves) occur when matter vibrates soil and mineral formations, which are sometimes detectable by humans. The seismic sensors extract wave reflections induced by targets (e.g., tanks, large personnel movements, and aircraft).

Seismic sensors classify targets as unknown, wheeled vehicle, tracked vehicle, or personnel by comparing seismic signatures of the potential target to known classified seismic signatures. Seismic sensors transmit detection and classification data through the sensor communications network to analysts who then perform target identification based on the characteristics of the detected seismic waves by comparing their wave signatures against known profiles [19]. Seismic data is then combined with other acoustic sensor information to enhance intelligence estimates concerning the position, the type of vehicle including the number of cylinders in the engine, the number of axles, the number of gears

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in the transmission and gear ratios, type of traction (wheeled or tracked), and the relative weight of the vehicle [2].

Seismic sensors are less susceptible to meteorological changes such as wind direction and speed, and humidity. Moreover, seismic sensors are also harder to deceive regarding vehicle weight because it is more difficult to make a heavy vehicle seem light by modifying its seismic signature [2]. When errors do occur they are principally attributed to soil composition (hard compacted soil is the best), moisture, temperature and layer depth changes resulting from weather, ambient interferences (i.e., noise due to earth tremors) and ground topology [2].
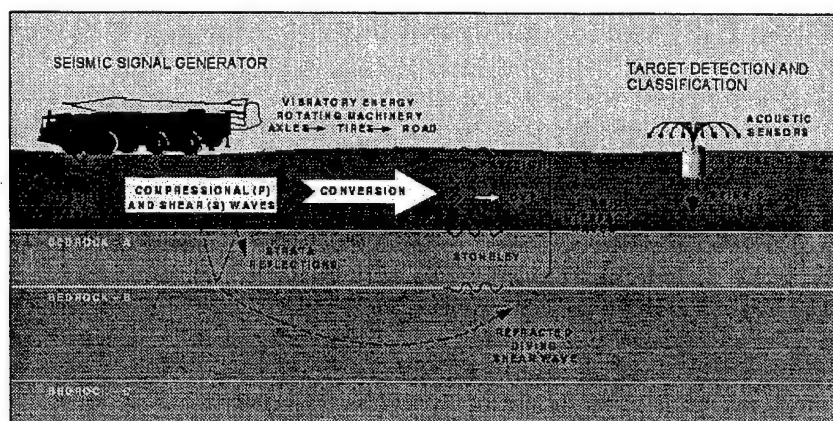
Figure 3: Seismic Detection and Classification Scheme [2].

2.1.3. Magnetic

The current suite of magnetic sensors provides passive, non-line of sight early detection and low-level classification of many battlefield targets. Their approximate operational ranges include a maximum effective range of 3 meters for personnel (provided the person is carrying a metallic object; (i.e., rifle, radio), 15 meters for wheeled vehicles and 25 meters for tracked vehicles. Again, magnetic sensors are omni-directions. The probability of detection is approximately 90 percent. The current suite of magnetic sensors does not possess an on-device classification capability [15]. They have a very short detection range, but are capable of classifying targets and cueing other higher resolution sensors.

Magnetic sensors operate by detecting changes in the ambient magnetic field (earth's magnetic field localized to that area) that are caused by the movement or presence of metallic objects (Figure 4). The fact that the Earth's magnetic field is omnipresent and magnetic sensors are relatively low cost makes this suite of sensors attractive for use in Objective Force design.

The Earth's magnetic field emits a uniform magnetic signature (10^{-3} to 10^{-1} Gauss) over a wide area (several kilometers) [8]. Magnetic sensors detect the presence, strength, and direction of magnetic fields based on disturbances in the local magnetic field. Magnetic sensors must gather data on the local magnetic field in the area of concern in order to compare it to target signatures. Vehicle size and composition affects the magnitude and duration of the magnetic pulse from the target source. Variation of these measures provides the basis for distinguishing between target types. If the magnetic sensors are not calibrated to the local magnetic field then, incorrect detection and classification is possible.

Ferrous Object + Uniform Magnetic Field = Field Disturbance
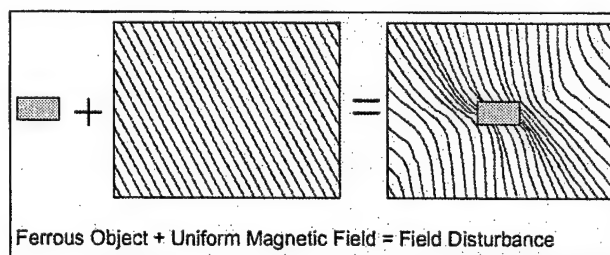
Figure 4: Metallic Object Disturbance in a Uniform Field [8]

Vehicle detections occur when a metallic object passes close to the magnetic sensor and the sensor captures the different dipole moments associated with various metallic parts of the vehicle. The field variation reveals a detailed magnetic signature that can be compared to known magnetic signatures. A group of magnetic sensor placed at fixed distances (e.g., 6 meters apart) analysts to calculate a moving target's speed by observing the magnitude of the disturbance curves. Doing so requires potential target vehicle lengths to be known beforehand as this parameter is a key input in the speed calculation from the classification step.
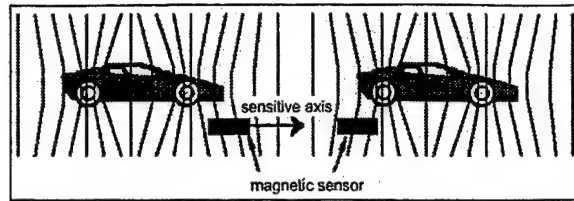
Figure 5: Direction sensing for Vehicles [8]

Calibrating the local earth's magnetic field (signature) is essential to the accuracy of the sensors as well as threshold levels for the various metallic object signatures because each signature is represented by a 3-dimensional plot whose individual axis values produce a synchronized waveform. Figure 6 depicts an actual 3-axes plot for three vehicles driving by a magnetic sensor at 1-, 3-, 5-second on the time axis. Each type of vehicle (A, B and C) is then classified using pattern recognition.
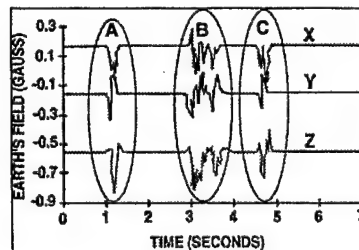
Figure 6: Three vehicle three-axes Magnetic Sensor Plot [7]

Distance from the sensor to the target can impact detection, classification, and direction of battlefield targets (Figure 7). Figure 7 illustrates rapid signal strength degradation as the distance from sensor to target is increased. One can observe that the effectiveness of magnetic sensors is dramatically reduced when this distance exceeds 10 feet. While appearing to present an obvious limitation, this phenomenon is actually very useful in that it provides a strong discrimination capability if one is attempting to detect several avenues of approach that are close together.
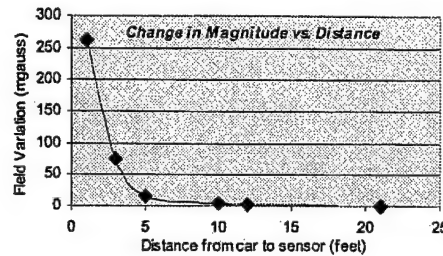
Figure 7: Magnitude change vs. field variation [8]

Power lines, earth tremors, and electric motors can all induce detection and classification errors in magnetic sensors. Magnetic sensors are not susceptible to weather (e.g., temperature, moisture), noise and ground topology, and are less susceptible to meteorological changes such as wind direction and speed, and humidity. Magnetic sensors are also difficult to deceive regarding vehicle length because it difficult to make a longer vehicle seem shorter by attempting to modify its magnetic signature unless the vehicle is composed in some clever way of non-magnetic materials such as composites.

2.1.4. Radar

The current suite of radar sensors provides 360-degree, *active*, non-line of sight detection and classification capabilities for a number of enemy battlefield targets. They are primarily used as moving target indicators but can detect stationary targets as well. Radar is used to detect the presence of an object at a distance, detect the speed of an object, and classify an object based on echo and Doppler shift principles. In contrast to the passive sensors described so far, radar sensors are active pinging sensors in which radio waves are transmitted into the air and then received when they have been reflected by an object in the path of the wave.

The operational ranges for radar sensors are 5 to160 meters (maximum detection) for a single person and 300 meters (maximum detection) for vehicles. These ranges increase if the sensors are configured for reduced detection zones (e.g., 45 degrees) [41]. Probability of detection and classification data is not available for radar sensors at this time.

Radar sensors operate by reflecting either pulsed radio waves (user defined) or continuous waves (1 revolution per second) off of distant objects and collecting the echo signature [9]. Distance to a particular target is ascertained by measuring the length of

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time between the sent and reflected signal. A radar sensor is capable of determining both a target's speed and whether the target is moving towards or away from the sensor by measuring the shift in frequency of the reflected wave in comparison to the sent wave. This shift is called a Doppler shift [5].

Radar technology operates in the microwave region (1 Gigahertz – 10^3 Gigahertz), which is above the radio wave and below the infrared regions of the electromagnetic spectrum.

Several topology and environmental factors affect the performance of radar sensors by bending or reflecting (attenuating) the radio waves. These include irregular terrain topography, weather and target characteristics. Irregular terrain topography can cause radar pulses to bend, extraneous blips to appear (false positive readings), and detection ranges to decrease. Reflected signal from weather phenomena (i.e., precipitation, clouds) greatly degrade or eliminate radar target detection and classification accuracy [14]. Dense objects and special absorption materials installed on targets and objects can mask object shape, thereby hindering classification.

After radar sensors receive a reflected signal from a potential target, the sensors form a signature of the potential target and compare that result to other known classified radar signatures. The sensor may pass the signature to other sensors (i.e., cluster or node sensor manager) for more complicated analysis (i.e., line of bearing). The resulting information is then transmitted through the sensor communications network and is combined with other sensor information (i.e., acoustic, seismic, and magnetic) at a single location at which an intelligence analyst can estimate the detected target's position. These analysts also perform target identification based on the characteristics of the detected radio waves by comparing their wave signatures against known profiles [19].

2.2. Sensor Cluster Concept

The individual sensor types discussed previously define an individual sensor node. Sensor nodes consist of either a single mode sensing type (e.g., seismic) or a multi-mode combination of sensors (e.g., seismic and acoustic). Technology improvements and enhancements have enabled the attributes of several sensors to be combined onto one

sensor platform. Individual sensor nodes grouped together define a sensor *cluster* (Figure 8).
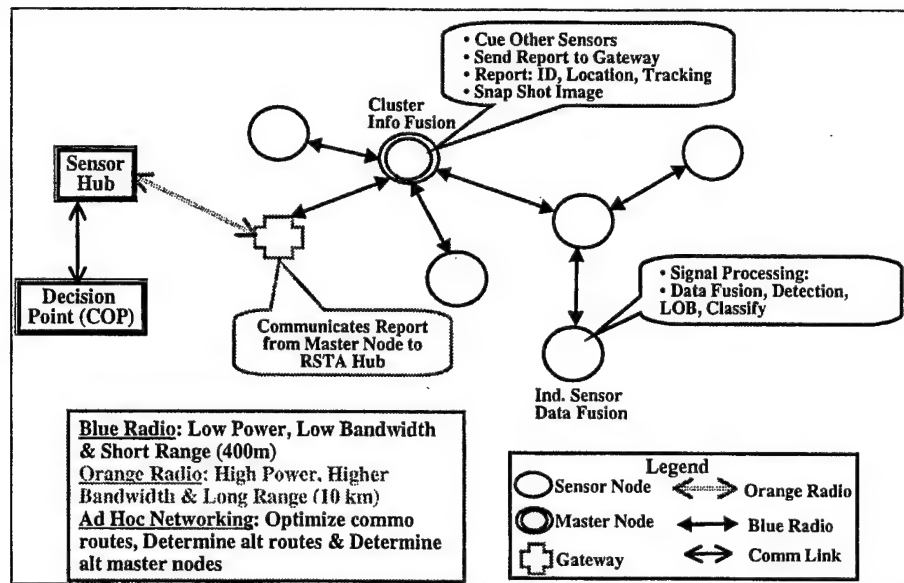
Figure 8: UGS Cluster Depiction

An UGS cluster covers approximately a 1 by 1 kilometer area of terrain. As depicted in Figure 8, each cluster is composed of three to five sensor nodes, a master node, and a gateway. The master node controls the cluster's internal operations and the gateway facilitates long range communications to entities outside of the cluster, such as a RSTA hub. The RSTA Hub is the station that receives, consolidates and processes all the reports from the various sensor clusters. Within a cluster, the sensor nodes communicate via short-range radio with an approximate 400-meter range capability and the cluster communicates to the RSTA Hub through the gateway via long-haul communications with an approximate 20-kilometer range capability [20]. The final information product is then displayed on a commander's common operating picture providing battlefield situational awareness and facilitating effective decision making.

Figure 9: UGS Cluster Operations

The operational activities involving sensor clusters can be described by a generic 8-step process [25], regardless of the type of sensor or sensors used to create the cluster. A graphic representation of this process is depicted in Figure 9. First, sensor nodes are deployed via some delivery means (i.e., air, artillery, hand-emplaced) that emplaces them into BLOS and NLOS areas of the battlefield. Upon physical emplacement, the sensors activate and begin self-testing communications within the cluster to determine optimal communications routing pathways. A master node is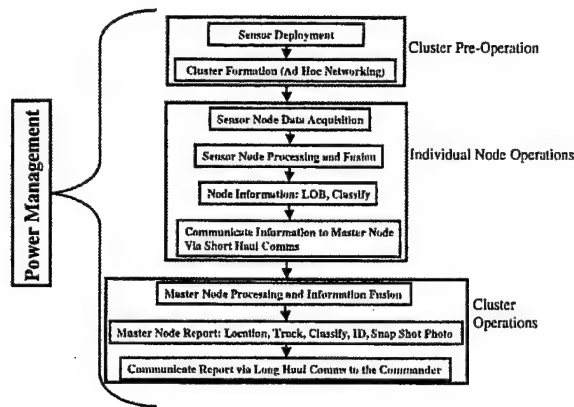 'elected' which will serve as the sensor node that translates low-level sensor data involving detection and classification into a single cluster report. The optimal communications routing topology is determined by pre-configured routing tables in the master sensor. These pathways are preset to insure a specified level of connectivity and redundancy is achieved by the active sensor communications network. Following this, the sensor cluster begins its assigned mission as programmed. The master node also controls the power management of itself and all of the other sensors in the cluster as well.

When detection occurs, the individual sensors perform very low-level data classification of the target, sending the resulting information to the master node. The master node receives and fuses the individual sensor information, which, in turn, prompts the master node to alter the power consumption mode of specific sensors ('wake-up') and possibly re-tasking them to perform actions that might increase the classification or identification probabilities of the detected target. The master node next fuses all of the information and sends a single cluster information report through the cluster gateway to the RSTA Hub.

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Multiple UGS clusters connected by a communications network make up a sensor *field*. While a cluster basically covers a one square kilometer area, many clusters are necessary to cover the typical area required in an UGS mission. The RSTA Hub consolidates all of the reports from the individual clusters of the sensor field in order to create a report for the whole sensor field. This report facilitates command decisions based on the enhanced COP and SA provided by the sensor field(s) deployed in the NLOS and BLOS areas.

The area of responsibility and the terrain in that area are key factors in determining how many clusters are necessary in each sensor field. It is important to note that not all sensor clusters must be interconnected in a sensor field. Sensor clusters can be placed at different locations on the battlefield operating independently of other sensor fields.
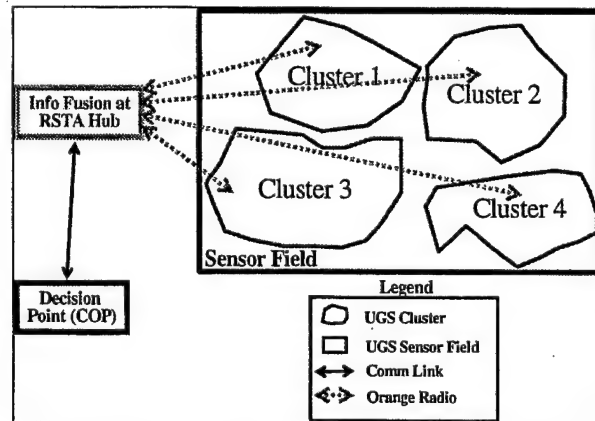
Figure 10: UGS Field Depiction

2.3. UGS Field Systems Analysis

It is impossible to conduct a tradeoff analysis for an UGS field without first gaining a solid understanding of the critical functions that a sensor field must perform in order to be considered a successfully designed system. In the systems analysis process, a *functional decomposition* and a *functional flow diagram* are the principle tools used to illuminate these critical functions. These functions become imbedded in a hierarchy that reflects the effective need, priorities and preferences of the major design stakeholders. This *value hierarchy* and its associated functions, objectives and evaluation measures

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then define the framework against which tradeoffs in performance metrics are properly considered.

2.3.1. Functional Decomposition

A functional decomposition helps one to understand the complexity and issues involved with the overall UGS system. The resulting relational diagram yields a comprehensive, well-defined list of the main functions and sub-functions required of the system. Figure 11 shows the functional decomposition for an UGS field. The boxes with dashed lines are the critical functions and sub-functions directly used in this study. The definitions for each of these functions and sub functions are listed in Table 2, Page 25.

Figure 11: Functional Decomposition

Table 2: Functional Decomposition Definitions

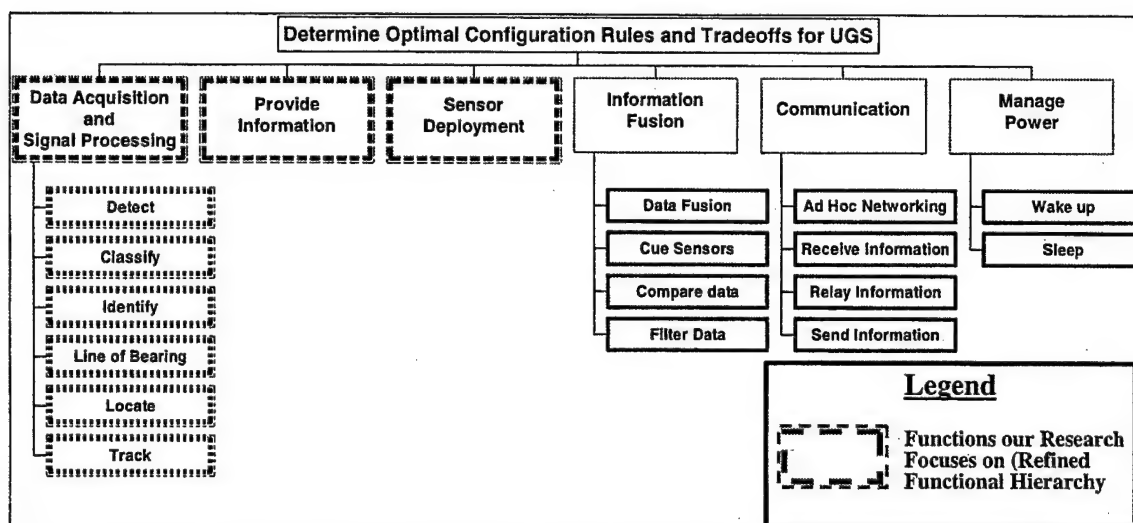|	
Data Acquisition & Signal Processing	The individual sensor picks up primitive data that may result in an enemy target being detected, classified, identified, located, and/or tracked and a line of bearing to the target is generated. The data is filtered and tries to improve the signal to noise ratio.
Detect	An individual sensor or the sensor network discovers or discerns the presence of enemy elements or targets in the area.
Classify	The individual sensor or the sensor network correctly classifies the target (i.e., wheeled, tracked, personnel) once it is detected.
Identify	The individual sensor or the sensor network correctly identifies (e.g., T-60 tank, BMP-2) the target once it is detected and classified.
Line of Bearing (LOB)	A LOB is a line from the sensor to the target with no distance information.
Locate	The sensor network combines LOBs from various sensors in order to provide a grid location of the target and its ranging information where the it was detected.
Track	The sensor network works together to follow a target and its movement through the sensor field once the target is detected and located.
Provide Information (for the purpose of Decision Making)	The usefulness of the information provided to the commander for the common operating picture. This function involves the amount of uncertainty in the sensor reports, the military utility obtained from the sensor fields and the impact sensor fields have on the overall unit mission.
Sensor Deployment	The requirements and process for placing sensors out on the battlefield.

2.3.2. Value Hierarchy

The UGS value hierarchy is a graphical hierarchical representation of the major functions, performance objectives and evaluation measures for the system. The topmost layer of the value hierarch represents the overall objective of the system. The next layer represents the major functions of the system. Associated with each function is an objective that specifies the ideal manner of performing the system function. Each objective is written in the form of maximize, minimize or optimize, thereby capturing the preferred direction of attainment or intent of the system. For this study, we chose to use optimize because the design goal is not always to maximize or minimize the stated objectives but rather to achieve an ideal equilibrium state that enhances system effectiveness.

At the end of each branch of the value hierarchy reside the individual evaluation measures that are used to assess the degree to which any competitive UGS system design achieves the function objectives. The evaluation measures are illustrated in brackets below the objective in Figure 12. Notice that four of the objectives do not have a

designated evaluation measure because more research is required in order to designate those evaluation measures.
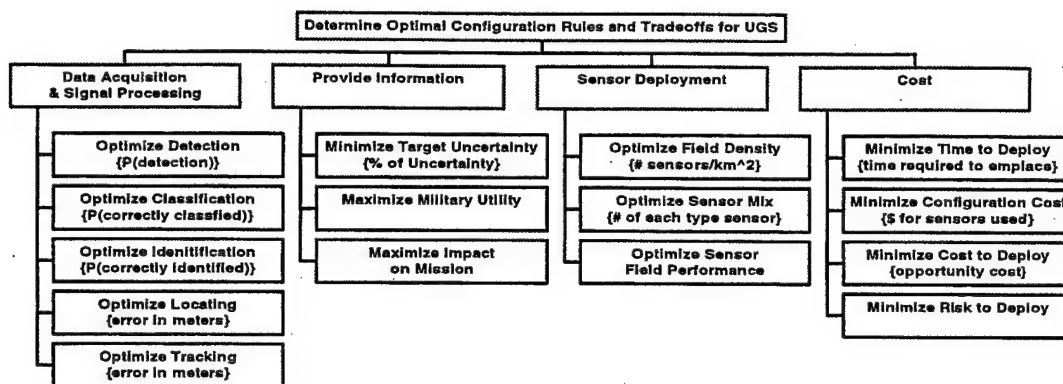

Figure 12: UGS Value Hierarchy

The terms not discussed in Table 2 and displayed in the Value Hierarchy (Figure 12) are defined in Table 3.

Table 3: Value Hierarchy Terms and Definitions

Configuration Cost	The total cost of the sensor cluster or field, depending on the focus level. The cost includes: gateway, sensor nodes and all other associated hardware.
Cost	A function of relative monetary cost, time for deployment, cost of deployment means, and opportunity cost for selecting deployment means.
Cost to Deploy	The cost to use a deployment mechanism to deploy sensors (takes into account lethality lost and manpower costs).
Sensor Density	The number of sensors, regardless of type and capability, per square kilometer in a sensor cluster.
Mission Impact	The positive or negative effects or aspects produced from UGS deployments and UGS field information gathering on the mission.
Military Utility	The impact or the amount of worth the addition of a sensor field plays on the overall unit's capabilities. In other words, the amount of use the unit gets out of the sensor fields.
Risk to Deploy	Risk is the measure of the probability and severity of adverse effects [18] and Risk to Deploy takes into account the loss in lethality while deploying sensors, the threat of loss of life to soldiers deploying sensors, the sensors giving indications and warnings to the enemy in reference to blue locations.
Sensor Field Performance	Performance of the sensor field (target detections, classifications, identifications, locating and tracking), as measured by mission success and thresholds set by the decision maker.
Sensor Mix	The number of each type of sensor per square kilometer (seismic, acoustic, magnetic).
Time to Deploy	The total time including time it takes to prep the deployment mechanism and the time to deploy UGS on the battlefield.
Uncertainty	The inability to determine the true state of affairs of a system [18]. For our purposes, uncertainty describes the possibility that the sensor field report on targets and locations is inaccurate. If the report states 80% chance of a T-80 tank at grid XY, then there is a 20% chance it is not a tank and it is not located at grid XY, this is the uncertainty.

2.3.3. Functional Flow

The UGS field functional flow process was already briefly discussed in the context of the generic sensor processing steps. Figure 13 depicts the specific UGS field process that illustrates the sequential execution of UGS system functions. The main tasks (Tasks 1-7) and sub-tasks are featured in this figure. Level one (high-level) functions are labeled in the flow diagram with the numbers 1.0, 2.0, etc. Sub-functions associated with each specific high-level function receive the same function number prior to the decimal and a function ordering number after the decimal point.
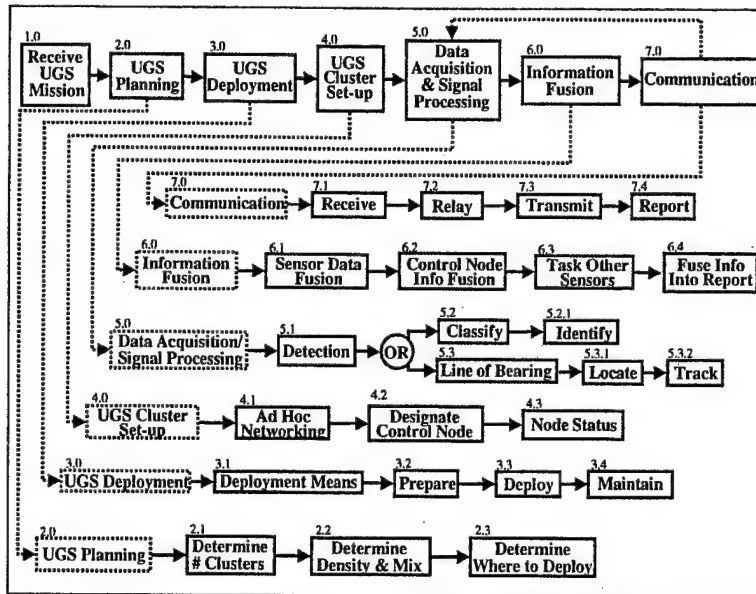
Figure 13: Overall UGS Functional Flow Diagram

Figure 14, Figure 15, and Figure 16 portray the sub tasks and sub-sub tasks for UGS Deployment (3.0), Data Acquisition/Signal Processing (5.0), and Information Fusion respectively (6.0), the three critical functions of the UGS system that support the tradeoff analysis developed in this study.
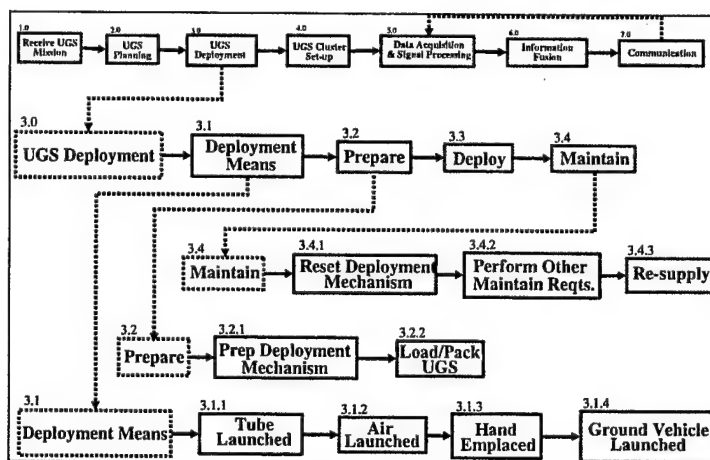
Figure 14: 3.0 - UGS Deployment Detailed Flow Diagram
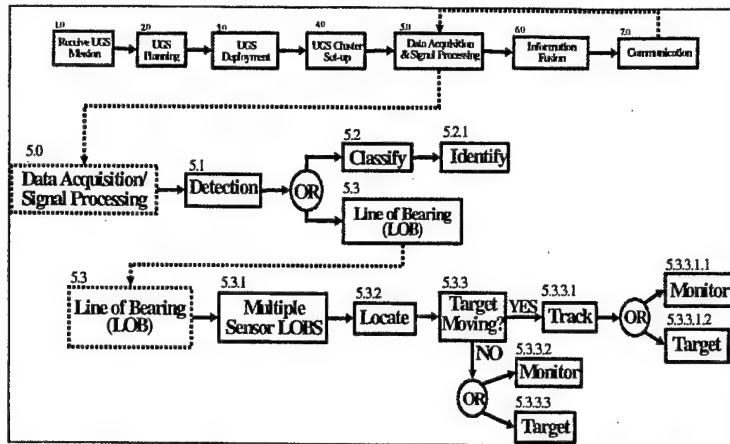
Figure 15: 5.0 – Data Acquisition & Signal Processing Detailed Flow Diagram
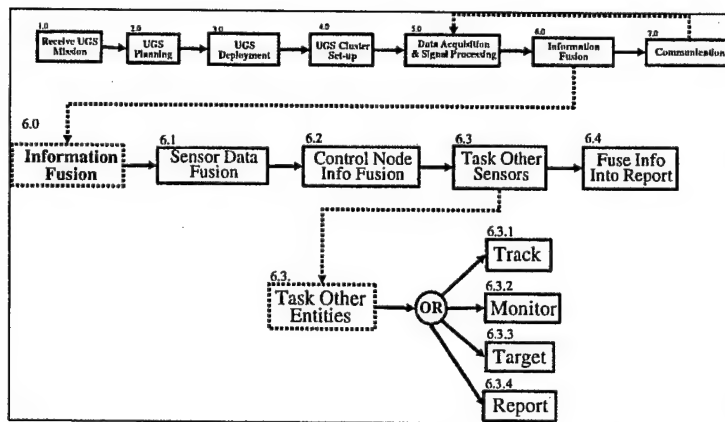
Figure 16: 6.0 – Information Fusion Detailed Flow Diagram

Section 3.   Functional Tradeoff Relationships

3.1. General

The specific performance measures used to assess the attainment of design objectives play an important role in this study because they will drive many of the deployment and management decisions concerning networked UGS. The issue of concern herein is the relationship that exists between each of these performance measures and the number of sensors that define a sensor cluster. Upon first consideration, one might be tempted to simply maximize all performance measures subject to cost limitations. Such a limited modeling perspective can mistakenly lead to an opinion that designers should place as many sensors in a cluster as desired because, after all, they are relatively cheap. The resulting bounding factors for such a design philosophy would be not wanting to flood the data flow channels and overcoming human limitations to process data.

We propose that a third and equally as important consideration should come into play: having "just enough" sensors in the cluster design so as to optimize overall performance and build in a buffer against device failure, yet not "over-investing" to the point of wasting resource allocation. It is with this latter motivation in mind that we examine the existence of points of diminishing marginal productivity on performance output measures for sensor clusters. We do so by first proposing functional relationships that exist between the number of sensors contained in a sensor cluster and the level of output in terms of each of the proposed performance measures.

3.2. UGS Cluster Level

At the sensor cluster level, we propose seven estimated theoretical tradeoff relationships: percent of the Area of Interest (AOI) covered versus sensor density, percent of Overlap in the AOI versus sensor density, error distance for locating targets versus sensor density, number of targets tracked at once versus sensor density, percent of the AOI covered versus cost, target locating error versus cost and number of targets tracked at once versus cost. These relationships all represent performance measures requiring two or more sensors present in a cluster.

Figure 17: % AOI Covered Versus Sensor Density portrays the performance output and marginal output functions associated with the measure percent of terrain covered in the base unit AOI versus sensor density. The performance output function for this measure illustrates
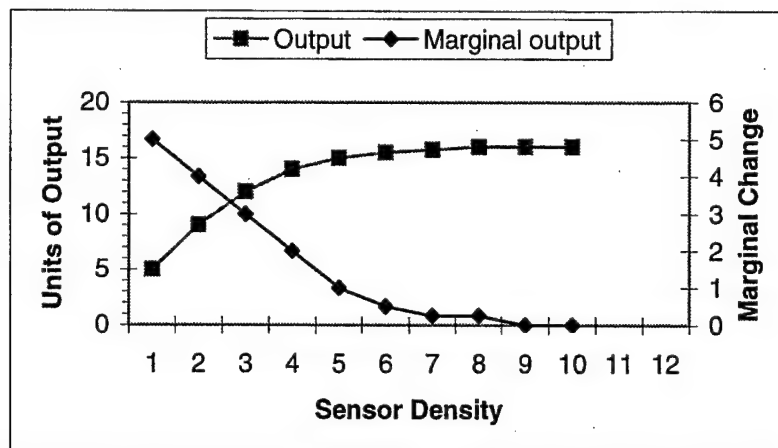
Figure 17: % AOI Covered Versus Sensor Density

the typical case where the percent of AOI coverage continues to increase but at a decreasing rate due to the boundary constraints on the base unit AOI. Once 100% of the base unit AOI is covered, no further increase in performance is possible. The marginal output for this performance measure clearly indicates this as well where, unlike the functional relationships that follow, we witness a monotonic non-increase in the marginal output of the cluster as the sensor density is increased. The ideal number of sensors for a cluster based on this performance measure would be driven by the first point at which the marginal productivity of the cluster falls beneath a small enough acceptability threshold. Setting this threshold acceptance value equal to 0, it follows that the cluster density should be set at 8, taking into consideration a buffer of 1 sensor in recognition of a 10% deployment failure rate.
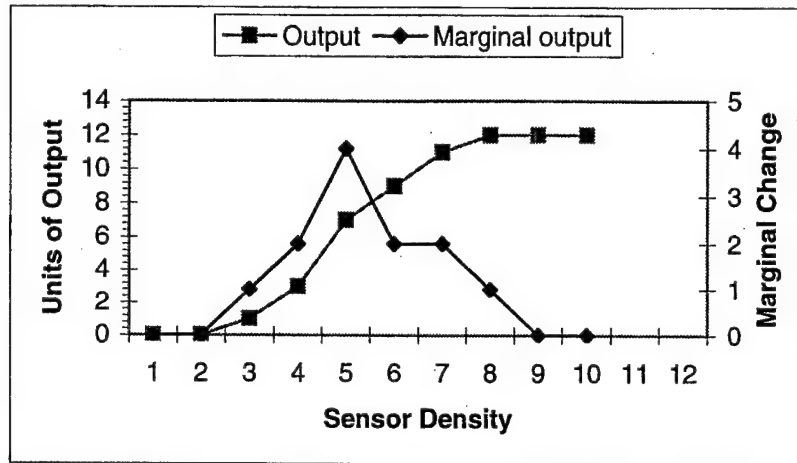
Figure 18: % AOI Overlap versus Sensor Density

Figure 18 displays the functional tradeoff relationship between percent overlap of two or more sensors in the base unit AOI versus sensor density. We note in comparison to the previous performance output measure that the percent of overlap increases at an increasing rate until the 5-sensor level. Afterwards, although the overall cluster output continues to increase, it does so at a decreasing rate. This behavior is clearly evident in the marginal output function that peaks at the 5-sensor level, diminishes in going to the 6-sensor level, and non-decreases between the 6 and 7-sensor level. The peak marginal performance output corresponds to the point at which the cluster performance output curve changes from convex to concave, as expected. It is this point that drives the ideal sensor cluster density based on the law of diminishing marginal productivity. Again, as in earlier, we would advocate a cluster density of 6, taking into consideration a 10% deployment failure rate.
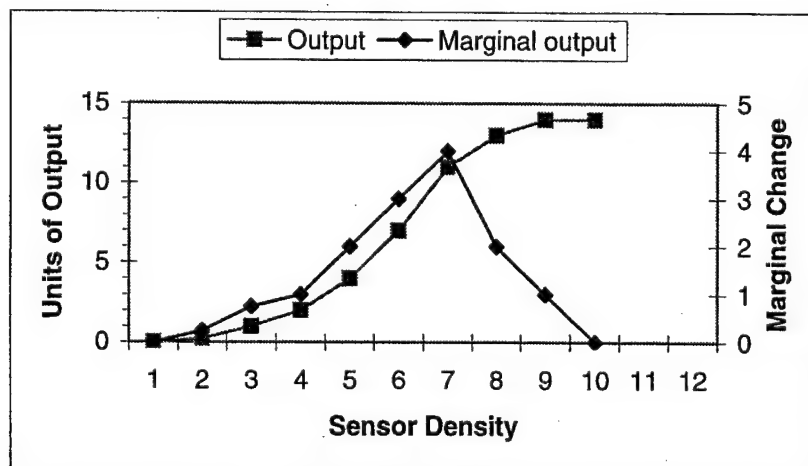
Figure 19: Locating Error versus Sensor Density

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Figure 19 displays the functional tradeoff relationship between locating error versus sensor density. Initially the rate of locating error increases to the 7-sensor cluster density, then the rate of increase diminishes until the rate is equal to zero at the 10-sensor cluster density. The underlying phenomena taking place here is that the error distance can not get any smaller due to technology/hardware error constraints. It is these constraints that impose the asymptotic limit on performance output seen in the locating error performance function. We would advocate a cluster density of 8 based on this tradeoff function, taking into consideration a 10% deployment failure rate.
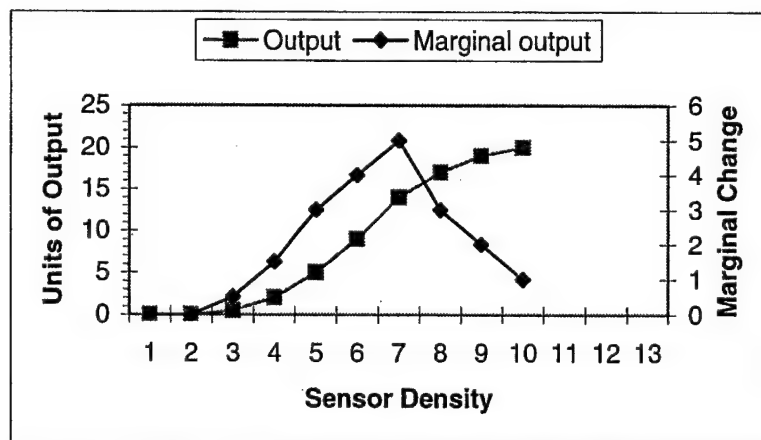
Figure 20: Tracking versus Sensor Density

Figure 20 portrays the functional tradeoff relationship associated with the number of targets the sensor cluster is able to track at once and sensor density. It is evident that as the number of sensors increases, the number of targets capable of being tracked within the base unit AOI increases as well up to the 7-sensor cluster density. It is again technology and/or hardware limitations that impose the effects of decreasing marginal productivity for this performance measure. A cluster density of 8 appears to be appropriate based on this tradeoff function, taking into consideration a 10% deployment failure rate.

For the next set of tradeoff functions, we use relative cost versus both percent base unit AOI covered and cluster target locating error in our proposed trade off relationships. In this sense, cost is envisioned as an aggregate variable representing relative monetary cost, time for deployment, cost of deployment means, and other associated opportunity costs.
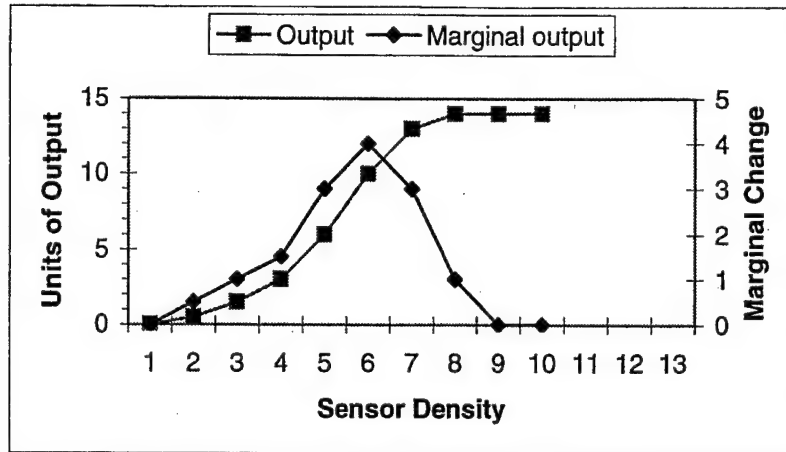
Figure 21: % AOI Covered versus Relative Cost

Figure 21 portrays the functional tradeoff relationship associated with the percent of AOI coverage in terms of cost. We can observe the effects of decreasing marginal performance occurring for this tradeoff function as the sensor density is increased from 6 to 7 sensors. We envision that the principal cost imposing this effect is by having to employ an additional deployment "package," in the sense of projectile packaging or air-deployed delivery systems. For the case of hand emplacement (which is not the most likely means of cluster delivery for BLOS and NLOS), we believe this effect is somewhat diminished because once troops are deployed to set up a sensor cluster by-hand in the base unit AOI, the principal costs of deployment have been realized. That is, the cost of having to emplace an additional sensor in relative close proximity to another emplaced sensor is not anticipated to be enough to significantly decrease the associated marginal output of the cluster. A cluster density of 7 appears to be appropriate based on this tradeoff function, taking into consideration a 10% deployment failure rate.
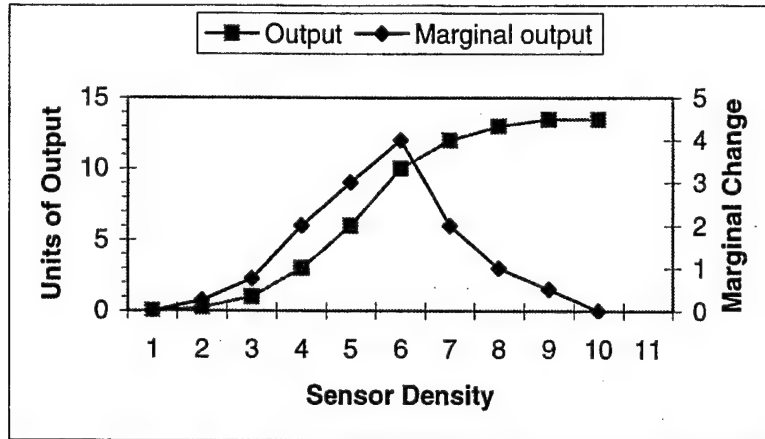
Figure 22: Target locating error versus Relative Cost

Figure 22 portrays the functional tradeoff relationship associated with the target locating error and cost. This graph portrays the lower the locating error, the higher the units of output. Locating error decreases as the sensor density increases up to a certain accuracy level. Based on numerous error possibilities in the lines of bearing and target locating techniques [44] the target locating error will not reach zero. At a certain point, the cost of adding an additional sensor results in a diminished improvement in the locating error. A cluster density of 7 appears to be appropriate based on this tradeoff function, taking into consideration a 10% deployment failure rate.
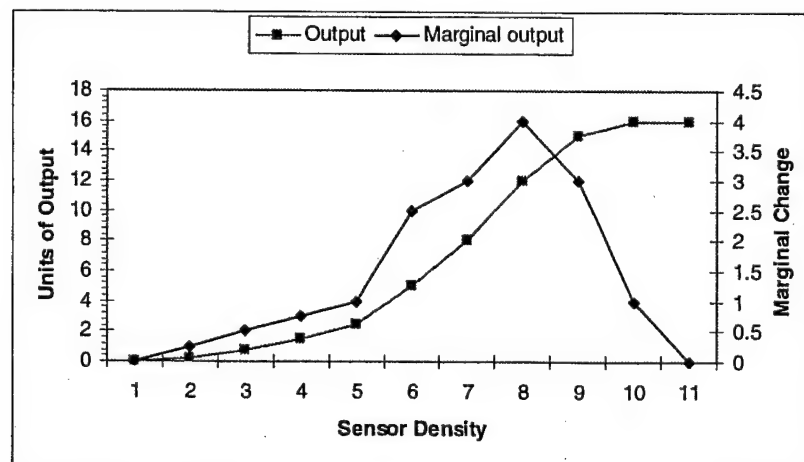
Figure 23: Target tracking rate versus Relative Cost

Figure 23 portrays the functional tradeoff relationship between the target tracking rate performance output of a sensor cluster and cost. Underlying this relationship is an assumption

that the more targets a cluster tracks, the higher the units of output. We recognize that the target tracking rate increases as the sensor density increases, but only up to a certain density level. The limited number of possible targets in a one-km^2 area, technology constraints for the maximum number of targets a sensor cluster is able to track and other error components introduced in the estimation of lines of bearing and target locating techniques directly imply that the target tracking rate will reach a maximum capability point. Beyond this point, the rate of performance output will diminish and the cost of adding an additional sensor results in very minor to no improvement in the target tracking rate. A cluster density of 9 appears to be appropriate based on this tradeoff function, taking into consideration a 10% deployment failure rate.

## 3.3. Tradeoff Validation

There were two tradeoff relationships we were able to reasonably validate with computational experimentation at the sensor cluster level: percent of AOI coverage versus sensor density and percent overlap coverage versus sensor density. Sensor density is an important performance measure because its level has a direct impact on several Objective Force resource allocation design parameters including cost per base unit cluster (in terms of device cost, maintenance, and deployment method), risk to the force (in terms of degree of situational awareness and deployment exposure), and information quality (in terms of data/information overload and degree of redundancy of information products) at the network level.

Initially, we intended to use the simulation results from the Future Combat Command and Control Two Exercise held in April 2002 at Fort Knox, Kentucky to validate our proposed tradeoff functions within the contents of this study. However, difficulties in extracting meaningful data mandated that this task be postponed until a further study. In short, the simulation software used at the Future Combat Command and Control Two Exercise did not incorporate functional expressions as the basis for the simulation. Rather, lookup tables were created using ARL's ABFA [50], [51]. Over 10,000 lookup tables were created based on different target types, terrain, and time of day. This large number of lookup tables and limited resources and time on our part hampered our capability to alter the sensor cluster density levels in the simulation so that the individual performance measure relationships could be experimentally determined. In its place we developed an Excel spreadsheet model to

demonstrate those individual sensor tradeoff relationships that could be reasonably tested in this environment.

The results from this initial testing begin to shape the ideal density level for sensors in an FCS cluster. The remaining relationships between clusters and between sensor fields and a plan to assess their accuracy is discussed in a later section. Although our study relegates the process of validation to future work, we believe that the framework we use in this study is appropriate for the purposes of design. Points of marginal decreasing productivity within the major sensor cluster performance measures as described herein should drive the decision on how many sensors to allocate to an FCS TOE package. The preliminary results in this study provide a benchmark against which future validation effort can be applied.

Throughout all of the performance measures we propose, we define the output productivity as the ratio of cluster output performance to the levels of sensor density. It follows that the average productivity of a sensor cluster is defined as:

$$\text{Avg Productivity}_{\text{cluster}} = \frac{\text{Total Cluster Performance Output}}{\text{Number of Sensors in Cluster}}$$

The marginal productivity of a sensor cluster is defined as the additional performance output realized as a result of adding one more sensor unit to the cluster with all other cluster inputs held steady.

Equivalently:

$$\text{Marginal Productivity}_{\text{cluster}} = \frac{\Delta \text{ Cluster Performance Output}}{\Delta \text{ Number of Sensors in Cluster}}$$

We can interpret the marginal productivity of a cluster in the following way. Over the range n to $(n + 1)$ sensors, each sensor in the cluster adds approximately $\text{MP}_{\text{cluster}}$ to the total performance output. Visually, the slope of the curve describing the relationship between the cluster performance output and the sensor density gets 'flatter.'

Since the proposed tradeoff relationships are based on discrete increases in sensor density levels, we model these marginal rates of productivity output using first divided differences [16]:

$$\text{First divided difference} = \frac{\Delta y}{\Delta x} = \frac{y_{n+1} - y_n}{x_{n+1} - x_n}$$

These first divided differences represent a discrete analog to the first derivative information typically used to assess marginal rates of return and points of diminishing return on investment in an economics application.

3.3.1. The Excel Spreadsheet Model

The overall goal for using the Excel spreadsheet model was to determine the ideal base unit cluster size to allocate to an FCS TOE package that targets a one square kilometer area of interest (AOI). In this model, one design goal was to maximize the overall sensor cluster coverage area within that AOI. During the simulation exercise noted earlier, the NVESD C4I/Modeling Simulation section used a sensor density of four (4) sensors within a given cluster in order to cover this size AOI within the simulation. We therefore wanted to investigate the interactions and interdependencies of a sensor cluster and to validate or refute the use of four sensors in the simulation conducted at Fort Knox based on the concept of diminishing marginal returns to productivity.

The Excel Spreadsheet model we developed is an adaptation of a simple detection probability model created by Roger Burk, Department of Systems Engineering, United States Military Academy. Burk's model principally focused on calculating the optimal layout of three sensors based on communication and sensor detection ranges. Figure 24 shows a two-sensor layout example using our Excel model. Each cell represents a 50 meter square area, the numbers in each cell indicate how many sensors in the base unit cluster are theoretically capable of detecting a target in that cell (*i.e.*, A "0" indicates that "0" sensors in the base unit cluster are capable of detecting a target in that cell, a "1" means "1" sensor node is capable of detecting a target in that cell and so on).
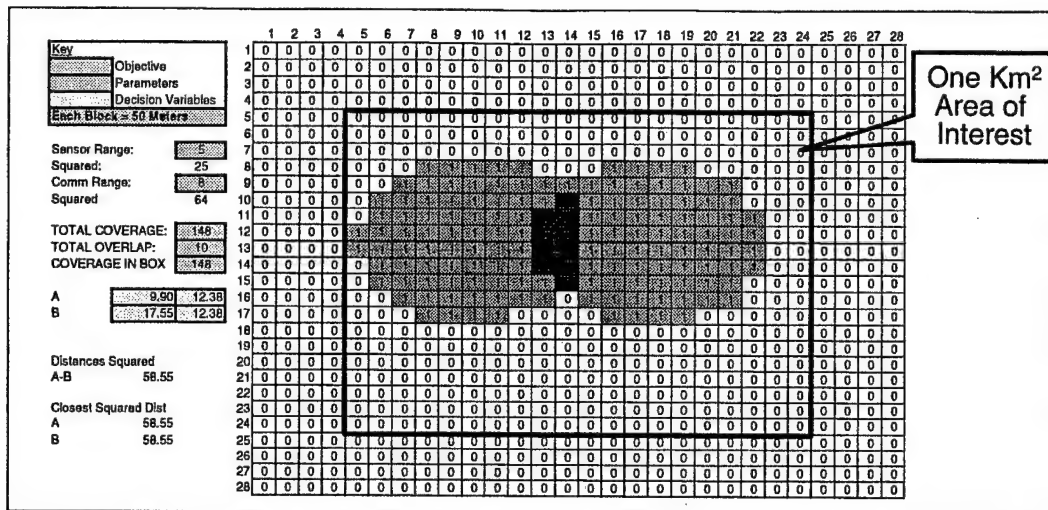
Figure 24: Excel Spreadsheet Layout Example with Key and Overview Information

The model attempts to maximize total coverage in the one square kilometer box by altering the *x*-values and *y*-values (physical location in a Cartesian plane; these also represent the decision variables) for each sensor node. The parameters used in this model include the sensor detection range (*i.e.*, "10" equals 10-cells multiplied by 50 meters which equals a 500 meter detection radius) and the communication range of the sensor nodes. The evaluation measures we used for this model included the percent of area covered in the base unit AOI and the percent of detection overlap that is covered by two or more sensors simultaneously. The flexibility to incorporate various other goals and design criteria is an attractive feature of this initial model. Thus, design goals and restrictions, maintenance and deployment costs, expanding the size of the base unit AOI, restricting the allowable number of sensors that can overlap coverage, and adjusting coverage to detect a specific type of enemy target (e.g., wheeled vehicles or personnel rather than heavy wheeled or tracked vehicles) can all be easily accommodated.

For this initial experimentation, we used the following design assumptions.

Assumptions:

- Only seismic sensors are being used in the cluster.
- Daylight operational timeframe is being used.
- AOI contains flat terrain with no obstacles (i.e., hill, trees, rivers).
- No radio interference exists to hamper intra-node communications.
- Hand emplacement of sensors is being used, which supports the modeling of location in known (x, y) coordinates rather than imbedding stochastically determined locations.
- Sensor reliability is equal to 1.0 (if they are present, they are working perfectly within their performance parameters).

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- Detection radius of an individual sensor = 500 meters.
- Communications range between sensors is at its maximum = 400 meters [20].
- Each Excel cell (e.g., G12) represents a 50 meter square area.
- We assume that no cell has partial detection coverage. That is, we disregard the asymmetrical coverage area that sensors propagate. A cell with more than 50% coverage is considered to have 100% detection coverage in this model.
- A 200 meter buffer area exists outside the base unit AOI to facilitate demonstrating the detection capability outside of the defined AOI.

3.3.2. Sensor Cluster Level Results

The results for the two relationships we examined are summarized in Table 4, with their associated graphics presented in Figures 24-27. Based on these results, which again only integrate the performance results of two of the seven performance measures we propose should drive the design level for FCS TOE, the ideal level of sensors to assign to a base unit cluster appears to be approximately five. In the Excel model, there is literally no gain in performance by increasing the cluster level from four to five sensors. However, as in the earlier case noted, hardware failures and deployment failures of approximately 10% justifies the higher of the two levels.

In comparison to the proposed tradeoff relationships simply estimated by a review of the literature, the 5 sensor level indicated by the Excel model is lower than the 7 indicated by % coverage and 6 indicated by % overlap noted earlier. Whereas this difference is not overwhelming, it underscores the earlier comment as to the need to validate the specific tradeoff functions with operational testing or simulation on a larger scale.

Table 4: Results Table for Each Sensor Density Tested in the Spreadsheet

# of Sensors	% AOI Overlap (%)	Rate of Change in Overlap (%)	% AOI Coverage (%)	Rate of Change in Coverage (%)
1	0		79	
2	40	40	87	9
3	61	21	98	11
4	77	16	100	2
5	83	7	100	0
6	97	4	100	0
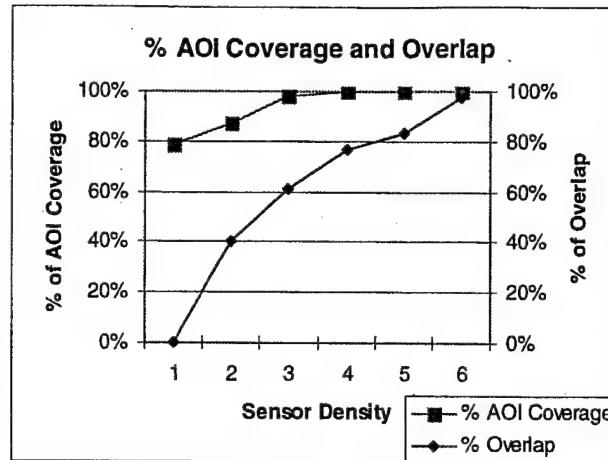
Figure 25: The % of AOI Covered and % of Overlap for each Sensor Density
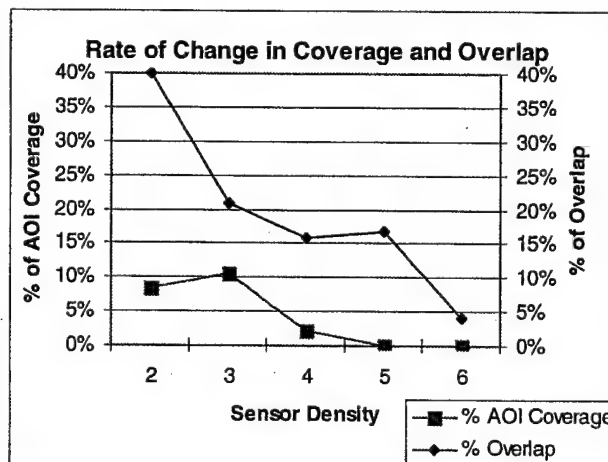
Figure 26: The 1st Divided Differences (Rate of Change in Coverage and Overlap)

Figure 26 shows the rate of change for both percent of AOI coverage and percent of overlap. For percent of AOI coverage, there is still some gain between four and five sensors, but not change between five and six sensors. For percent of overlap, there is a slight increase in the rate of change between for and five sensors and there is still some rate of change between five and six sensors, but less than 5 percent.
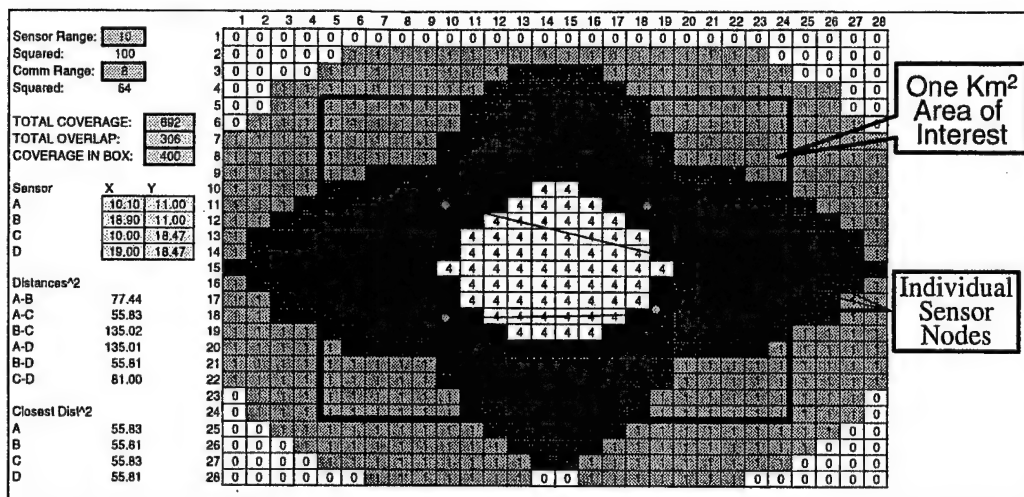
Figure 27: Four Sensor Layout and Coverage Results
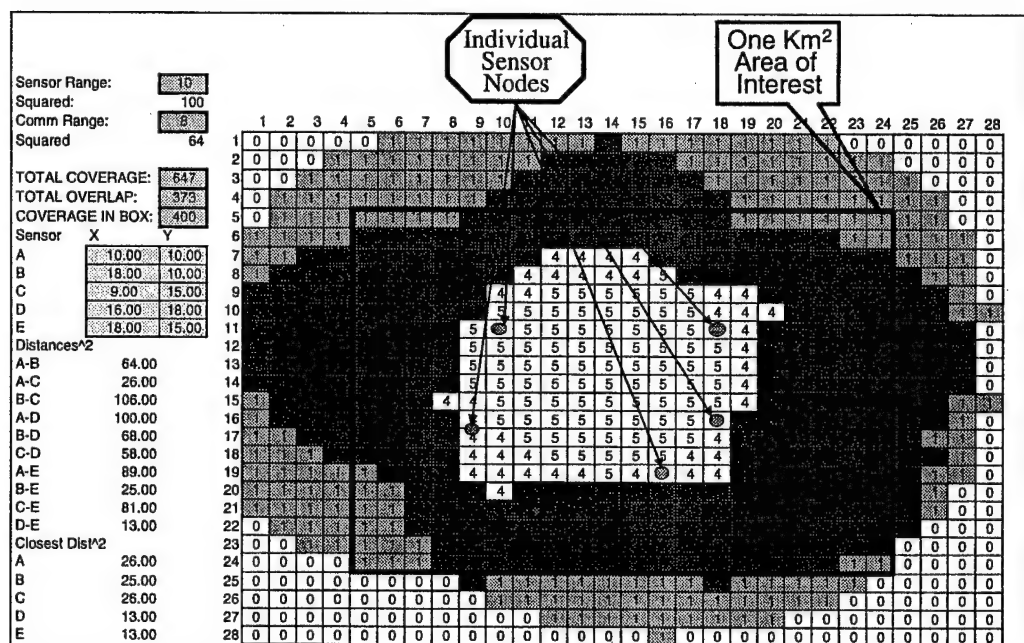
Figure 28: Five Sensor Layout and Coverage Results

Section 4.   Validation Process
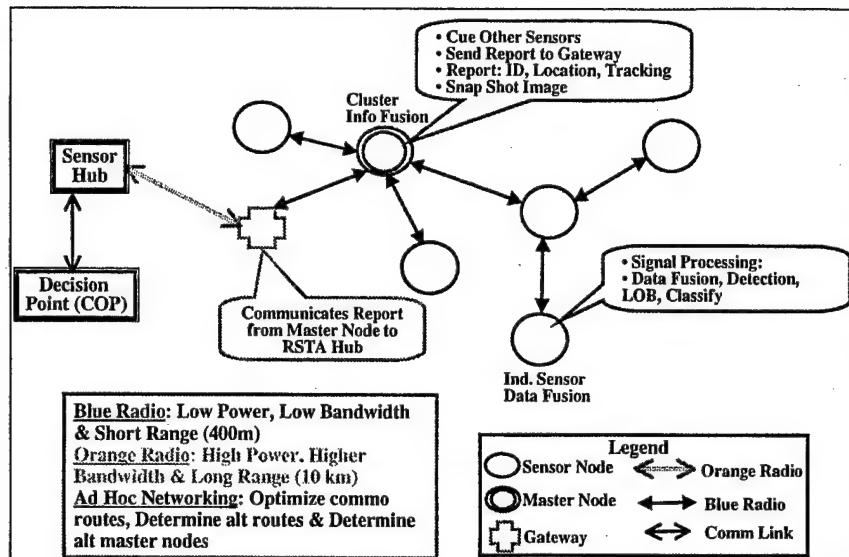
Figure 29: UGS Cluster Depiction

4.1.   Overview

This paper presents a methodology for determining networked UGS tradeoff relationships and determining points of diminishing marginal productivity as a means of identifying efficient and effective sensor allocation levels for Objective Force TOE design. This section presents the validation process we recommend in order to more accurately determine the shapes of the functional tradeoff curves.

4.2.   General Simulation Requirements

To validate the functional tradeoff relationships proposed in this study, equivalent performance data need to be generated and analyzed by either constructing a human-in-the-loop simulation such as that used in the Future Combat Command and Control Two Exercise noted earlier, or actual sensor experimentation in a field environment If a simulation is going to be used that is similar to that employed during the Future Combat Command and Control Two Exercise, we recommend several modifications to this simulation to include features capable of directly producing the needed validation data.

In the existing simulation, there is no distinction made between sensor-types allocated to the base unit clusters. Such a limited capability prevents modeling cluster sensor densities even

for the case of a base unit cluster containing only a single type of sensor. Furthermore, it precludes the use of the existing simulation to experiment with various mixtures of sensors possessing different performance parameters within a single base unit cluster, an issue of intense interest to Objective Force designers. Lastly, the performance output information presented to the human-in-the-loop should not consist of simply a color-coding of red, yellow, and green in order to present the state of information passing out of a cluster to the decision point.

We recommend that the simulation be adjusted to accommodate and distinguish between a minimum of three basic types of sensor clusters on the battlefield: acoustic, seismic, and magnetic. Real time switching between these three types would enable the simulation to model sensor nodes with multiple modalities (*i.e.*, both seismic and acoustic) simply by switching on command between which mode is active.

We further recommends that programmers associate with each sensor cluster type a different waiting time between the information request event started by the user and the delivery of information back to this user on the screen. Presumably, this wait time should be based on some empirical data concerning the technical specifications of the sensor types and their ability to process and transmit information. Additionally, and perhaps most importantly, when the sensor situational information is displayed on the screen, programmers should include the certainty level of the information, conditioned upon the source of this information. Perhaps this is done with a simple tagging of a percentage next to the sensor field information provided on the screen. This displayed certainty information could be based on the detection probabilities stated for each sensor type for a given weather and battlefield situation. Ideally, it would be based on an analysis of the stochastic component makeup of the final information product for a particular sensor type and a particular sensor network configuration.

For a particular mission (which has to be captured as well), what is the frequency distribution (*i.e.*, how many times does the decision maker use each of the sensor fields noted? When faced with having to pay a cost in terms of waiting time for higher quality (*i.e.*, less uncertain) data, what are the commanders' evolving preferences (what do they actually do in practice)? How long are they willing to wait? Are commanders willing to make fire/no fire decisions based on faster, but lower quality information provided by one type of sensor, or do they prefer to wait for slower, higher quality information provided by another? How often? And for what range of certainty will they do this (by sensor type)?

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Each sensor cluster should receive a definition and a name or number in order to keep track of that individual cluster's performance. Furthermore, each sensor cluster should be dedicated to an AOI either in NLOS or BLOS, depending upon the deployment decision of the commander and the capabilities of the associated Objective Force to deploy and recover these mines.

4.3. Specific Tradeoff Requirements

4.3.1. Sensor Density

The performance measure *sensor density* is defined as the number of sensors per square kilometer. The simulation must be able to document the sensor density for each sensor cluster and sensor field (if used). Within each sensor cluster and sensor field (if used) the required validation data:

- Sensor Density
- Number of detections and number of total targets that pass through the AOR (Probability of detections = {(number of detections)/(number of actual targets)})
- Given a detections: The Number of targets correctly classified and number of classification attempts made (Classification Rate = {(number of correct classifications)/number of classification attempts)})
- Given a correct classification: The number of targets correctly identified and the number of identification attempts made
- Individual target locating and tracking capabilities: The error distance in meters for where the sensor says the target is and where it actually is for each target location report (average locating error in meters)
- Multiple target locating and tracking capabilities: The number of targets the sensor field is able to locate and track at one time (the total number of targets in the sensor field versus the number of targets the sensor field is able to track at one time)

4.3.2. Sensor Field Costs and Payoffs

The simulation should keep track of the various costs and payoffs for each sensor field. The costs will be estimates and require the capability to make comparisons between the costs and the performances of each sensor cluster or field. The payoffs will be estimates as to how much better a sensor cluster or field performs compared to a unit with no UGS clusters or fields.

4.3.3. Costs

In order to determine the various costs, it is hard to determine actual dollar amounts, so the simulation needs the capability to determine if the associated costs are low, medium or high. Examples of some of the various costs:

- Cost of Sensor Field Hardware (low, med, high)
- Cost of time to deploy Sensor Field (low, med, high)
- Cost to deploy Sensor Field (low, med, high)
- Opportunity costs:
  - ➢ Equipment time spent deploying sensors instead of using lethality (low, med, high)
  - ➢ Soldier time spent deploying sensors instead of normal mission (low, med, high)

4.3.4. Payoffs

Some of the associated payoffs that the simulation must be able to determine include:

- Timeliness of Intelligence (compare intelligence gathering timeliness to a unit without UGS and a unit with UGS)
- Quality of the Intelligence (percent of uncertainty associated with the reports)
- Number of Soldiers the sensor clusters or fields replace - (logistics train to soldier {LP/OP} compared to a logistics train to the sensor clusters or fields)

4.3.5. Sensor Field Performance

This section requires accomplishment by two means: measuring the actual response of commanders in the heat of battle and by surveys/interviews at the end of each battle. The more meaningful data will be if one is able to measure or record commanders' responses in the heat of battle.

Some of the simulation requirements for measuring sensor field performance include:

- For a particular mission (which has to be captured as well), what is the frequency distribution (i.e., how many times does the decision maker use each type of sensor fields?
- When faced with having to pay a cost in terms of waiting time for higher quality (i.e., less uncertain) data, what are the commanders' evolving preferences (what do they actually do in practice)?
- How long are they willing to wait? Are commanders willing to make fire/no fire decisions based on faster, but lower quality information provided by one type of sensor, or do they prefer to wait for slower, higher quality information provided by another? How often? And for what range of certainty will they do this (by sensor type)?

4.3.6. Military Utility

Military utility is very important when it comes to determining the amount of UGS to use on the battlefield and validating the tradeoff relationships for UGS. The simulation must be able to capture the following information:

- Do the UGS Sensor Fields provide adequate coverage of the Area of Operations (AO)?
- How much did the addition of UGS fields increase the AO?
- How much does the addition of UGS fields impact the scout's area of influence?

4.3.7. Mission

Units perform a number of different mission types. Are UGS necessary for all missions? The simulation needs to be able to capture the various missions that UGS are used in and how well they perform for each mission. One must be able to determine if the user uses UGS differently for each mission type and what those differences are. The simulation must be able to capture the following information:

- Is there one type of mission that is an absolute must for the use of unattended ground sensors, or are unattended ground sensors useful for all types of military missions?
- Do different types of missions require different quality or amount of information from the UGS fields? Examples include: 1) Is there a mission that only requires the UGS field to report a detection and classification; or 2) Does the commander need to know as much as possible, detection, location, identification and track, no matter what the mission of the UGS field.

Section 5.   Conclusions and Future Work

5.1.   Conclusions

Providing a methodology for future researchers and developers concerned with the deployment levels and use of Networked Unattended Ground Sensors is a valuable contribution to the Future Combat System of Systems team and anyone else concerned with the use of UGS on the battlefield. We outlined a number of other researchers and their work relating to this paper, provided an introduction and information on the different UGS types and their strengths and weakness, presented a number of tradeoff relationship ideas and showed the process for validating them and finding the points of diminishing returns for each tradeoff relationship. We also presented a process for validating the tradeoff relationships by laying out the requirements for a sensor simulation program to answer all of the necessary fact finding questions necessary to perform the tradeoffs we discuss.

We recommend that all FCS type applications require a methodology for systematic problem solving that demands modeling to identify tradeoffs and functions and quantitative analysis.

5.2.   Future Work

The area of networked unattended ground sensors, specifically sensor tradeoff relationships is a very diverse and unchartered field of research; therefore there are a number of areas for future research. We propose only a small portion of the immense amount of future research that exists in this area. The future work section presents four different categories for future work: 1) Research; 2) Simulation; 3) Tradeoff Validation; and 4) Deployment levels.

5.2.1. Research

There is still a great deal of research required. Specifically, interviews with the users to find tradeoff relationships important to them, developing any new tradeoffs that result, updating and changing current UGS capabilities and characteristics, communicating capabilities and limitations of the UGS clusters, accuracies of the UGS themselves (i.e., accuracy of LOBs, classifying), redundancy issues and needs for each cluster, and susceptibility to enemy deceptions and counter measures.

Interviews of the users, specifically battlefield commanders, allow the analyst to determine important measures of effectiveness and to subsequently accurately portray tradeoff relationships that are important to the users. During the interviews, the analyst also needs to find out priority and preferences for each of the different measures of effectiveness. Obtaining this information elevates the analyst to the next level as far as finding answers to this research problem.

Researching and developing accurate communication capabilities for the sensors clusters is essential. If the UGS cluster is unable to accurately and efficiently send reports via communication links to the people who need the information, the sensors are no good. Further research needs to be accomplished in this area such as determining how to ensure reports reach their destination, the accuracy or reliability that the report is still in its originally transmitted format, the enemy can not intercept and decipher the transmissions, and transmission speed of the reports.

Redundancy issues must be researched further. Redundancy issues that must be addressed include: 1) Are the sensor fields cheap enough to risk failure of the gateway node, or should there be multiple gateways in each cluster and how many; 2) If one sensor node fails is the cluster still effective; 3) If sensor clusters are fired in by rockets and mortars, how many sensor nodes are going to land and be effective at their mission; and 4) What redundancy requirements exist to ensure the cluster is still effective.

Research must be accomplished in the area of enemy deception and susceptibility to enemy sabotage. Research questions to address include: 1) Are the sensor nodes and clusters easily susceptible to enemy sabotage; 2) Can the enemy intercept radio transmissions from the sensor clusters and determine friendly forces' locations by analyzing radio traffic patterns; 3) Can the enemy decipher the message communications and determine what we know about them; and 4) Once the enemy locates the senor cluster, how easy is it for them to trick the sensors and perform deception tactics resulting in false reports from the sensors.

5.2.2. Simulation

NVESD modeling and simulation division currently has the CMS2 simulation package, which has a good start towards developing the necessary tools to answer the requirements we presented in Section 4 Validation Process. They are constantly working to improve their

simulation package. We have their simulation installed in the Department of Systems Engineering. One major task for future research is to learn this package and run experiments on our own. These experiments will provide some of the information we require. Unfortunately, there is still a lot of work that must be done on the simulation to make it more user friendly and allow easy access to data and results.

Developing a simulation that possess the capabilities to accurately model UGS clusters and fields as well as possess the capabilities to capture and provide output for the required information areas as presented in the validation process section is an absolute must for future research to be successful in this area. The simulation outputs must answer the important questions (presented in Section 4 Validation Process) and be easily accessible to the research analyst.

5.2.3. Tradeoff Validation

All of the tradeoff relationships for both sensor cluster and sensor field levels need further development and validation. The tradeoff relationships currently developed at the sensor cluster level include: percent of the Area of Interest (AOI) covered versus sensor density, percent of Overlap in the AOI versus sensor density, error distance for locating targets versus sensor density, number of targets tracked at once versus sensor density, percent of the AOI covered versus cost, percent of targets classified correctly versus cost, percent of targets identified correctly versus cost, target locating error versus cost and number of targets tracked at once versus cost. The tradeoff relationships currently developed at the sensor field level include: Quality of Intelligence (percent of certainty) versus Wait Time, Quality of Intelligence (percent of certainty) versus Mission Type, and Military Utility versus number of soldiers required. A number of additional or different tradeoff relationships will result from interviews and conversations with the actual users and battlefield commanders. Modeling the tradeoff relationships to exactly what the users feel is the most important is essential.

5.2.4. Deployment Levels

Two of the six objectives for this study were not accomplished and they are presented as future research projects: 1) Identify equivalence points between personnel and sensor clusters within the context of the typical mission set (intelligence) for the RSTA squadron and 2)

Prescribe ideal deployment levels and TOE assignment levels for general force configuration guidelines.

5.3. Stochastic Components

There are stochastic (probabilistic) components associated with the data generated at each individual sensor and the various information handling processes throughout a sensor network that remain unresolved by the time the information products reach the decision point. These components can appear as error rates, detection probabilities, classification errors, truncation of information due to aggregate voting processes, and the like. Information does not flow from origin to destination without undergoing various fusion processes (sorting, aggregation, concatenation, comparison against tabular thresholds, etc.) along the way. The quality of the subsequent decision made based on these information products is a direct function of the uncertainty imposed on this information in transit.

Three research issues are currently under investigation pertaining to this concept. First, for any general configuration of sensor network networks and sensor types, including airborne, seaborne and human-mounted, how much uncertainty is present in the final information product presented to the common operating picture at the decision point in the sensor network? If, for example, fire/no fire decisions are being made on information that, although it appears to be accurate in its representation, contains a high degree of uncertainty, then the decision quality suffers.

A second issue requiring investigation relates to the level of uncertainty that *should* be present. This is a critical design issue that has been overlooked to-date and one whose answer can be approached through simulation. The fact of the matter is that military commanders are quite willing to make decisions on information that is less than 100 percent certain as long as they trust the system providing this information.

It is possible to quantify this range and then to translate this range into design acceptability levels for configuring STS networks by presenting tags of "percent certainty" along with sensor field data at various stages in a human-in-the-loop simulation. By recording the players' responses to these levels, having them experience success and failure because of decisions based on this information, and letting them evolve to whatever operational range at

which they feel confident in taking action would provide valuable insights into their comfort range limits.

Once this range is identified and compared with the uncertainty levels present in UGS-based STS networks, for example, we can begin to effectively communicate to commanders an understanding of how the information provided by a sensor network compares to that available in their current operational practices involving decision-making. This goes to the heart of the issue of trust that must eventually be addressed.

Lastly, there exists an irrefutable inertia in the R&D community to respond to military needs for battlefield information by providing high quality image data directly to the common operating picture (COP). This response has increased the need for bandwidth, placed yet unresolved data fusion demands throughout information networks, and led to higher and higher development costs. Despite the promise of high-resolution image, in practice commanders are simply not satisfied with a single image regardless of its resolution. In fact, we discovered in a meeting with researchers from the ARL and NVESD that commanders frequently request more than five images prior to deciding to commit fires on the battlefield.

This underscores our conjecture that subjective measures of believability and reliability are *process* issues of concern to the users, not product issues. Experimentation needs to be conducted to validate or refute this conjecture. One method for doing so would be build into a simulation the ability to assemble and present to players high quality information that supports situational awareness from a host of simpler, less resource intensive sensors. The conjecture would be strongly supported if players obstinately preferred lesser quality sensor information provided by image sources over the higher quality information being provided in the aggregate by other sensor types. If time delay components representing the gap between request and delivery of information were included in this experimentation as well, and the players were again willing to wait for lower quality image information despite the operational costs blue forces realized in the interim period, the conjecture would be further strengthened.

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Appendix: List of Acronyms

A	
ABFA	Acoustic Battlefield Aid
ARL	Army Research Lab
B	
BLOS	Beyond Line of Sight
C	
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CMS^2	Comprehensive Mine and Sensor Sever
COP	Common Operating Picture
CSL	Combat Simulation Lab
F	
FASCAM	Family of Scatterable Mines
FCS	Future Combat System
FCSS	Future Combat System of Systems
FLIR	Forward Looking Infrared
G	
GEC	Generic Entity Controller
L	
LOB	Line of Bearing
LOS	Line of Sight
N	
NLOS	Non-line of Sight
NVESD	Night Vision and Electronic Sensors Directorate
O	
OneSAF	One Semi-automated Forces
ORCEN	Operations Research Center
OTB	OneSAF Test Bed Baseline
P	
PDU	Protocol Data Unit
R	
RSTA	Reconnaissance, Surveillance and Target Acquisition
S	
SA	Situation Awareness
SAF	Semi-Automated Forces
SE	Systems Engineering
SEDD	Sensor and Electron Devices Directorate
SEMP	Systems Engineering and Management Process
STS	Sensor to Shooter
T	
TOE	Table of Equipment
U	
UAV	Unmanned Aerial Vehicle
UGS	Unattended Ground Sensor
UGV	Unattended Ground Vehicle
UofA	Unit of Action
USMA	United States Military Academy
W	
WEBS	Warrior Extended Battlespace Sensors

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14. ABSTRACT

As the Army transforms itself into the 21st century, a number of new requirements arise in response to the need for a lighter force that is more rapidly deployed. The concept of trading heavy forces for information requires a substantial increase in the need for situational awareness and use of sensor technologies for remote reconnaissance collection on the battlefield. High quality situation awareness can be achieved using various types of networked sensors to flow information to a common operating picture console at the battlefield commander's disposal. Networked unattended ground microsensors (UGS) represent an integral part of the US Army's capabilities for covering Beyond Line of Sight (BLOS) and Non-line of Sight (NLOS) areas.

This report presents a methodology for understanding the relationships that exist between critical performance measures associated with UGS sensor clusters and the levels of sensor density in such a cluster. Using the concept of diminishing marginal output productivity in the face of constrained operating environment, this methodology can help Objective Force designers make informed decisions concerning the UGS base unit TOE package.

Following a detailed discussion of related work and technical information pertinent to this study, we present an in-depth systems engineering functional decomposition and functional flow analysis that illuminates many of the functional interdependencies affecting cluster design. Based on this analysis, we next introduce both the new methodology along with estimated functional tradeoff relationships and marginal output functions for various cluster performance measures. Finally, we introduce a process for validating the proposed tradeoff relationships in concert with several key information requirements for a human-in-the-loop simulation designed for such a purpose.

The new methodology presented in this study enables FCS Objective Force researchers to gain a new perspective on the interdependencies and interconnectedness of the UGS systems and demonstrates an effective means of identifying the appropriate UGS TOE levels for this force.

15. SUBJECT TERMS

Networked Unattended Ground Sensors, UGS, sensor field, micro-sensors, sensor cluster, sensor tradeoff study, battlefield sensors

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